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PROGRESS REPORT

GUST SIMULATION IN A WIND TUNNEL

by

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Langley Research Center
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FOREWORD

This report contains the results of the first six months' effort under NASA Grant NGR 44-001-036. The work was funded by the Aeroelasticity Branch of the Langley Research Center and was monitored by Mr. A. G. Rainey, Chief of that Branch.

ACKNOWLEDGMENT

Although a single name is listed as having authored this report, many people have had a part in producing the data which formed the basis for the report and in that sense are co-authors.

Dr. George L. Huebner of the Department of Meteorology provided invaluable advice and assistance in the area of instrumentation.

Mr. Robert J. Carr conducted most of the wind tunnel tests and Mr. Horace Comfort assembled the injector air supply system. Special mention must be made of Mr. Larry Morse and his skill in fabricating the hot wires and Mr. Benny Smith who worked with the signal detection and amplification gear.

Efforts ranging from plumbing to data reduction and plotting were done by aerospace engineering students James Dalton, Jesse Holster, Rex Aikman, Thomas Armatta, Jimmie Savage, Charles Osburn, and George Cain.

The contributions to this study made by the above individuals are gratefully acknowledged.

ABSTRACT

Initial studies of the use of air injection nozzles to produce simulated gusts in a wind tunnel are reported. Longitudinal gusts were produced at frequencies above 50 c.p.s. with amplitudes of 5.5 f.p.s. in an 83 f.p.s. stream. At lower frequencies gusts with amplitudes up to 21 f.p.s. were produced. The frequency response charactersitics of the injector-tunnel system were measured. Upstream injection was much more efficient than was downstream injection. Further studies are planned.

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Introduction

The influence of atmospheric processes on the design and performance of aerospace vehicles has been increasing. This can be attributed to several factors, among them the increased flexibility of the vehicle structures, increased flight speeds, increased use of low altitude airspace, and increased aircraft operations in bad weather.

The structure of a modern high speed aircraft is quite elastic and, as a result, changes in air loads such as those produced by atmospheric turbulence can induce oscillatory loading of the structure leading, in some situations, to structural failure. Spacecraft operations, particularly during the launch and pre-launch phases can also be influenced by atmospheric turbulence and wind shear. An unloaded launch vehicle, sitting on the launch pad, is quite flexible; as a result high stresses can be induced by ground winds. The loads may be oscillatory in nature because of their association with vortex shedding. These processes, in turn, can be substantially influenced by the launch vehicle configuration, the presence of gusts in the air moving over the vehicle, nearby structures and the adjacent terrain.

In order to study these processes in a laboratory environment it is desired to find ways of simulating turbulence, discrete gusts, and wind shears in a wind tunnel of sufficient size to permit testing of structurally similar models of launch vehicles and aircraft. It is obviously desirable to produce these processes in a measurable, controlled, and repeatable manner.

There are several ways in which one might go about this. Various types of vanes, screens and the like have been used to produce these atmospheric processes; however, all seem to suffer from one or more limitations. Mainly, the limitations are either in the frequency or amplitude of the induced discrete gusts or in the inability to separate transverse and longitudinal gust components.

This report describes the results of initial attempts to use air injection techniques to induce pure longitudinal oscillations in a wind tunnel stream, coupled longitudinal and transverse (e. g. sinusordal) gusts, random turbulence, and wind shears. The results contained herein were produced during the first six months of a one year study program sponsored by the National Aeronautics and Space Administration's Langley Research Center under NASA Grant NGR 44-001-036.

Thus far attention has been directed at (a) calibrating the wind tunnel and assembling instrumentation for the gust study; (b) installing and testing the initial air injector configuration. From these studies it was possible to determine those parameters to be used in evaluating an injector system and to use these results as a basis for specifying other configurations. Generally, it was desired to produce gusts at frequencies up to 50 cycles per second (c.p.s.) and amplitudes of the order of 10 feet per second (f.p.s.).

Experimental Apparatus

(a) Wind Tunnel

The basic facility used in this study was the Texas A&M University (TAMU) 2 foot by 3 foot Low Speed Wind Tunnel (2x3 LSWT). This facility, shown in Figure 1, has been used for student instruction in wind tunnel technology. It is a conventional fan-powered, closed return type subsonic tunnel with a speed range from 60 f.p.s. to 100 f.p.s. The flow quality in this facility is not especially good for precise aerodynamic studies; the turbulence level in the tunnel stream was about 1.5 percent and was high frequency. However, the flow quality was adequate for the present study where attempts were being made to induce low frequency turbulence (gusts) of the order of 10 percent. The comparatively small size and wood construction of the tunnel facilitated the installation of the air injectors in the test section. Additionally, the configuration was such as to permit the use of the results in defining an ejector system for use in the TAMU 7 foot by 10 foot Low Speed Wind Tunnel.

Flow calibration data for the 2x3 LSWT are presented in

Figures 2, 3, 4, and 5. The first three of these figures include contour plots showing the variation in velocity over the test section at 82 f.p.s. for the three locations designated, for example, by Station 24, meaning 24 inches downstream from the test section entrance. Figure 5 shows some values of the turbulence level in the basic wind tunnel stream at various points in the test section.

The tunnel air speed control was based on conditions measured using a 10-tube total pressure probe hooked to a sloping (13 degrees) water manometer to measure the air velocity at Station 12 on the tunnel centerline. The air velocity was controlled manually by adjusting the voltage applied to the fan motor. The velocity was monitored using a Pace Engineering Corporation Model CD51, 0.10 psi range pressure transducer, the signal from which was recorded on a Honeywell self-balancing potentiometer which had an 11-inch record span. The transducer, controller, and speed indicator-recorder are shown in a photograph in Figure 6.

The transducer was arranged to sense the difference between static and total pressures near the test section entrance and, therefore, was actually a dynamic pressure (q) indicator. This arrangement allowed this fundamental similarity parameter to be reproduced with reasonable accuracy, i.e., to an equivalent velocity error of approximately $\pm$ 1.0 f.p.s. The transducer sensitivity was adjusted so as to spread the presentation of the air velocity over the entire excursion range of the potentiometer. Thus far data have been gathered at three levels of air speed, namely, 70 f.p.s., 83 f.p.s. and 97.8 f.p.s., based on sea level standard density.

(b) Injector System

The air supply system used to drive the air injectors consists of a 2000 cubic foot tank in which dry air is stored at pressures up to 115 psia. A nominal 4-inch piping system carries the high pressure air through a pressure regulator to the injectors. In the static operation, that is with the injectors operating but with no modulation, the regulator system maintained pressure levels near 25 psia to within 0.5 psi over periods of 15 to 30 seconds.

Modulation of the air supplied to the injectors is the fundamental technique used in this study to induce oscillations of the wind tunnel stream. The modulation system used thus far is shown in Figure 7 and included two 1.5-inch ball valves, each having a port diameters of 1.0-inch, whose stems are connected. The valves were rotated with a 5 horsepower motor-pulley-belt system at rotational speeds up to approximately 30 revolutions per second. Since two pressure pulses were emitted each time a valve rotated, pressure pulses were produced at the injectors at frequencies near

60 cps. Some slippage of the drive belt occurred, depending on the air load on the valve, thereby causing some variation in the maximum frequency obtained during the tests. Evaluation of the actual frequencies was accomplished from records of high response pressure transducers installed in the injector air supply lines.

The configuration of the injectors is one of the major variables of this investigation. The nozzle array which has been used to obtain the results reported herein consists of four 2-inch exit diameter nozzles which had a design Mach number of 2.0. The position of the nozzles in the wind tunnel is shown in Figures 8 and 9. The arrangement in which the nozzles were directed downstream was designated Configuration A (Figure 8) while the upstream - directed arrangement was designated Configuration AU (Figure 9). This basic injector configuration was selected for the investigation of the fundamental characteristics of the air injection technique. In the later phases of this study the nozzle arrangement will be varied to attempt to determine the optimum configuration.

The ball valves were used as received with no attempt to modify the ball configuration to tailor the shape of the pressure pulses. Oscillograph records showed these pulses to be roughly sinusoidal, therefore, this configuration was judged acceptable for these initial studies. It is planned to modify the valve balls later in the study to improve the pressure pulse configuration.

Approximately 3 feet of nominal 1.5-inch pipe carried the air from the modulating valves to the nozzles. The attenuation of the pressure pulses caused by this length of pipe has not yet been investigated. While it would no doubt have been best to have the valving at the injectors, practical considerations precluded this type of installation during the initial phase of this study. However, some study of this problem has been completed and it appears possible to develop special solenoid valves, installed at the nozzle entrance to modulate the air supplied to the nozzles.

It can be seen (Figure 7) that the piping system used in this study was relatively crude and not designed to be aerodynamically "clean". Again, the emphasis of the present research was to study several air injection methods, making desirable the use of conventional piping units for ease of assembly and modification.

In the nozzle arrangement used in most of the work reported here the valve stems were arranged so that all nozzles were pulsed in phase, thereby producing variations in the longitudinal velocity of the wind tunnel stream. The valve stems were rearranged for some tests such that the two nozzles on the left side of the test section were pulsed 180 degrees out of phase with the two on the right side. This induced combined transverse and longitudinal variations in the stream.

(c) Research Instrumentation

The instrumentation used to operate the wind tunnel has been discussed above; this section contains a discussion of the devices used to sense and record the air injector system operation and its effect on the tunnel stream.

The air pressures in the piping leading from the modulation valves to the nozzles were measured with two Consolidated Electrodynamics Corporation (CEC) Type 4-313 transducers and two Dynisco Corporation transducers. One CEC transducer had a range of 15 psig while the other three were 100 psig range units. The CEC transducers have a frequency response characteristic which is flat to within 1/2 db at frequencies up to 1000 cps. The response characteristics of the Dynisco transducers were not known but their general configuration led to the conclusion they possessed relatively high response capability, adequate to follow the 50 cps pulses expected in the present study. Operational comparison with the CEC transducers as a reference has confirmed this conclusion.

Signals from these transducers were recorded with a Honeywell 1508 Visicorder oscillograph which was fitted with six Type M100 and six Type M-5000 galvanometers. These galvanometers had flat frequency responses of 0-60 cps and 0-3000 cps, respectively. All pressure transducer signals were fed to the M100 type galvanometers. The transducers were excited using a Hewlett-Packard Model 721A regulated power supply producing a nominal 8.0 volts. The signal span of the transducers was controlled by attenuating this excitation voltage so as to produce a maximum galvanometer trace deflection of 2.0 inches, thereby assuring a nonlinearity of less than 1.0 percent in the signal recording and reduction.

The transducers were calibrated using a mercury manometer at pressures up to 20 psig, except for the 15 psig range CEC transducer. Calibration results are presented in Figures 10, 11, 12, and 13. Check calibrations were performed twice during testing reported herein and indicated that the original calibrations were repeated to within $\pm$ 3 percent. It is concluded that the measured pressures in the piping leading to the air injectors were accurate to approximately $\pm$ 5 percent. Some inprovement in this figure is expected with the acquisition of new signal control and conditioning equipment which was delivered near the end of the reporting period.

Velocity fluctuations in the test section were measured using hot wire anemometers of conventional configuration. Four standard Flow Corporation wires, 0.0005 inch diameter and 0.060 inch long, and one crossed-wire probe, fabricated at Texas A&M, have been used. The crossed-wire probe has the two wires arrayed at 90 degrees from each other and swept 45 degrees. The wire signals were produced with a Flow Corporation Model HWB power supply-calibrator-amplifier unit. The amplified (volts level) hot wire signals were recorded simultaneously with a Tektronix Type 502 dual beam oscilloscope and on the Honeywell oscillograph where it was fed to a Type M100 galvanometer through a G51A Triad transformer to remove the DC component of the signal. This arrangement allowed the oscilloscope to be used to record not only the low frequency fluctuations produced by the injector system but also the higher frequency turbulence present in the stream. By simultaneously recording the signal on the oscillograph it was possible to relate the character of the induced stream velocity fluctuations to the injector pressure modulations. The oscillograph was normally operated at a record speed of 10 inches per second with timing lines every 0.1 second. Oscilloscope data were recorded with an attached Polaroid camera in the usual manner.

An estimate of the accuracy of the hot wire results is somewhat difficult to determine. Flow Corporation calibration data were used. Based on these data, the characteristics of the signal conditioning and recording gear, and the errors introduced in the data reduction process, it was estimated that the velocity fluctuations were probably determined to an accuracy of ± 5.0 to 7.0 percent of the value of the fluctuation.

The mechanical vibration of the wires was examined by recording their signals with the modulation valve operating but with no air moving through either the valves or the tunnel. In general this mechanically induced signal was less than the noise level in the hot wire signal and therefore was ignored. The noise was random and was easily taken into account in the data reduction process, especially from the oscillograph records where the low response galvanometer filtered out the high frequency signal and the recording of several cycles allowed an average response to be evaluated.

The determination of the velocity fluctuations from the hot wire signals was accomplished in the usual fashion; the theory and utilization of hot wires can be found in many publications.[1,2] The data reduction procedure used in this study followed primarily the procedures of Reference 2.

Velocity fluctuations were detected using the constant current technique and computed based on "square wave" calibration and the modified King equation for heat transfer rate from the wire.

$$Q = K(T-T_e) \left[0.97 + 1.82\ (P_r R_e)^{1/2}\right] \qquad (1)$$

where Q = heat transfer rate

K = coefficient of thermal conductivity

T = equilibrium heated wire temperature in the stream

T_e = equilibrium unheated wire temperature in the stream

P_r = Prandtl number

R_e = Reynolds number, based on wire diameter

Making use of the observation that for air $\frac{K^2}{\mu T}$ where μ is the viscosity, is essentially independent of pressure and temperature, the above equation can be written in the form

$$Q = (T-T_e)\ f\ (pV) \tag{2}$$

where f(pV) is a function of the pressure-velocity product.

If one considers the velocity V to be made up of an average velocity $\overline{V}$ on which a fluctuating component v is superimposed, and a corresponding description of the wire resistance

$$R = \overline{R} + r \tag{3}$$

it can be shown that in order to determine the instantaneous velocity it is necessary to measure not only the instantaneous output voltage from the wire but also the instantaneous rate of change of output voltage. By using a compensation network in the hot wire signal amplifier the amplifier output signal, e_1, can be related to the wire output and its time derivative.

$$e_1 = K_1\ e + K_2 \frac{de}{dt} \tag{4}$$

The constants K_1 and K_2 can be determined from an electrical calibration wherein a square wave voltage variation is applied to the wire and the corresponding wire outputs recorded.

Postulating the use of amplifier compensation and square wave calibration the equation relating the ratio of fluctuating velocity to mean velocity to the wire and amplifier characteristics is

$$\frac{v}{V} = 4\left(\frac{i}{I}\right)\left(\frac{e_1}{e_{1S}}\right)\left[1 + \frac{0.58}{6.6\ \sqrt{p^*\ v^*\ D^*}}\right] \tag{5}$$

where

i = square wave current passed through the wire

I = time average wire current

e_1 = wire signal voltage change due to turbulence

e_{1S} = wire signal voltage change due to square wave calibrator

p^* = pressure in atmospheres

V^* = air velocity in hundreds of feet per second

D^* = wire diameter in thousandths of an inch

In the present work e_1 and e_{1S} were measured from the oscilloscope and oscillograph records. The currents, i and I, were computed or read from meters or settings on the hot wire control unit. The p^* was always near atmosphere, the V^* was either 0.70, 0.83, or 0.978 f.p.s., and D^* was always 0.5 thousandths of an inch.

The crossed wire probes were at an angle of 45° from the steady stream vector thus the V of equation (4) becomes 0.707 V for the crossed wire probe. Similarly, the measured v was taken perpendicular to the wire. The measured longitudinal velocity variation was coupled with the data taken with the 45° wire to determine the transverse velocity fluctuations.

Typical Test Procedure

The data which have formed the basis for this report were gathered in the following fashion. First, the hot wire probe was arranged in the desired position and its operation checked at low current levels. The t unnel was started and brought to a specified velocity, for example 70 feet per second.

With air moving past the hot wire the wire current was increased, thereby raising the sensitivity of the wire to velocity flucuations. Then the square wave calibrator was activated and the wire output recorded on both the oscilloscope and oscillograph. Following the calibration record, the calibrator was turned off and a record made of the basic turbulence level in the stream.

Next, with the air supply valve off, the modulation valves in the injector system were rotated to the open position, then the air supply valve was opened and the pressure regulator adjusted to bring the steady state ejector pressure to one of three settings in the range from 15.5 psia to 18.5 psia. Then the modulation valve actuator motor was turned on and set for an injector pulse frequency near 8 cps. At this setting an oscilloscope record of the hot wire signal was made, while the same signal and three or four injector line pressure transducer outputs were recorded on the oscillograph. After this record was made the modulation valve actuator setting was changed to give a pulse frequency near 17 cps and the signal recording repeated. Data was usually taken at three other frequencies, 30 cps, 42 cps, and 55 cps. As explained above there were some variations in the actual frequencies obtained because of slippage of the belt which drove the modulating valves due to non-constant loading on the valves.

The opening and closing of the modulation valves caused unsteady processes in the air supply line which resulted in injector peak pressures which differed substantially from the static values set with valves open. The maximum injector pressures ranged from 18.5 psia to near 25 psia and transducer records indicate a varying frequency response characteristic as was expected. This is discussed later in relation to the velocity fluctuations produced.

Results and Discussion

From the work completed thus far it is possible to arrive at several conclusions concerning the air injection method. These conclusions and the data and analysis supporting them are presented in separate sections below.

Longitudinal fluctuations by downstream-facing injectors

A drawing of injector configuration A was presented in Figure [illegible]. This configuration was examined at stream velocities of 70 f.p.s.

and 97.8 f.p.s. with three different injector pressure levels. Frequency response data were obtained using a hot wire perpendicular to the stream and in the horizontal plane on the centerline at Station 24. Some typical test results are presented in Figures 14 and 15.

The records of pressures made in three of the four injector supply lines indicate that the injector pressure pattern was not a smooth sinusoidal variation but has one or more minor fluctuations superimposed on the main pulse. This was probably caused by the configuration of the ball-type modulation valves and could no doubt be improved by modifying the straight-through hole configuration in the ball. This was not regarded as a major problem considering the exploratory status of the research and, therefore, was left for later study and refinement. More basic questions regarding the air injection method were in need of study and could be answered using the non-sinusoidal pulses produced by the off-the-shelf valves.

The oscillograph records in Figure 14 clearly demonstrate the frequency response characteristic of the fluid system which is the 2 x 3 LSWT. The hot wire signals at a low pulse frequency of 8.46 c.p.s. (Figure 14A) show a velocity fluctuation amplitude of 1.24 f.p.s. Upon increasing the frequency to 17.33 c.p.s. with the injector pressure range constant, the velocity fluctuation dropped to a barely discernable 0.21 f.p.s. and increased to 1.03 f.p.s. at 26.0 c.p.s. At 31.0 c.p.s. the amplitude increased to 1.24 f.p.s. and, at 38 c.p.s. dropped to 1.03 f.p.s. Note that while there was some variation in the injector pressure, there is no pattern which indicates an association with the Δv variation.

Longitudinal flucuations were produced in a stream which had a basic velocity of 97.8 f.p.s. Some typical results are presented in Figure 15, and fundamentally, the results are similar to those at 70 f.p.s.

The frequency response characteristic can be caused by two factors. One, the injector air supply system is a pneumatic system which, itself, has a response pattern which may cause the injector nozzle efficiency to vary with frequency. Two, the wind tunnel return circuit can transmit pulses into the test section entrance, thereby affecting the velocity fluctuations induced there.

In order to examine these two possibilities, a test was made at a tunnel speed of 97.8 f.p.s. wherein the injector pressures were near those in the 70 f.p.s. test shown in Figure 14. It was thought that by operating the tunnel at somewhat different velocity, the circuit "tuning" could be altered, however, it must be recognized that the greatest velocity change was in the test section; the large cross-section portions of the tunnel would undergo only a slight change in velocity.

The results are presented in Figure 16A and indicate that the alteration of the tunnel speed slightly affected the frequency response characteristic. Some of the data taken at 70 f.p.s. at various injector pressure levels is shown in Figure 16B. Based on this rather small amount of information it appeared that the tunnel velocity was more important than the injector system in determining the frequency response of the system.

Additional study and analysis of this problem is presented later in the discussion of the Configuration AU results.

One of the interesting results of the data presented in Figure 14 is related to the high frequency turbulence in the tunnel stream. The oscilloscope records presented include measurements made in the stream before and during air injection. These data indicate that the addition of injected air to the tunnel stream did not substantially alter the high frequency turbulence level in the tunnel. This can be observed from the hot wire signals taken prior to the activation of the air injection system.

Based on the available data it must be concluded that configuration A was not an especially efficient configuration in terms of velocity increment induced for a given injector pressure. This is especially evident when compared with the velocity changes induced by configuration AU, the upstream-direction version of configuration A. The experimentally determined relationship between injector pressure and induced velocity is shown in Figure 17.

It is worth noting that at an injector pressure of 18 psia the total injector flow was approximately 3/14 pounds of air per second while the flow through the test section at 70 f.p.s. was approximately 31.1 pounds of air per second. Therefore the injected mass flow averaged about 10 percent of the basic tunnel flow rate.

Longitudinal fluctuations by upstream-facing injectors

Configuration AU is shown in a drawing presented in Figure 9. The data shown in Figure 18 are typical of the performance of this system and, for equivalent conditions of stream velocity and injector pressure, exhibit larger velocity fluctuations. The frequency response pattern was roughly similar to that for configuration A. At a stream velocity of 83 f.p.s. the test data presented indicated that the velocity fluctuation amplitude was 21.4 f.p.s. at 8.6 c.p.s., decreased to 7.38 f.p.s. at 19 c.p.s. and remained roughly constant at all frequencies up to 54.0 c.p.s. At the highest frequency a low frequency "beat" appeared at about 0.5 c.p.s. and an amplitude at 18.0 f.p.s. The average injector pressure variation ranged from 18.7 psia to approximately 24.35 psia.

The injector pressure records show some non-uniformity at the lower pulse frequencies but generally improve at the higher frequencies. It is apparent that at high frequencies the induced velocities are not as uniform (sine-like) as were obtained with configuration A. Although each injector pulse induced a corresponding response from the stream, the low frequency "beat" was superposed on the higher frequency pattern. The hot wire used to obtain the data presented in Figure 18 was located at Station 24 on the tunnel centerline, therefore it was 18 inches from the injector nozzle exit and could have been affected by the injector air.

To examine this possibility the wire was moved to Station 12, test results are shown in Figure 19 and indicate that the uniformity of the simulated gusts is improved at a frequency of 40.5 c.p.s. but the low frequency "beat" remained with much the same amplitude but with the frequency increased to approximately 6 c.p.s. Other tests at somewhat lower injector pressures indicated that the amplitude of the "beat" was substantially reduced and the high frequency (47.3 c.p.s.) fluctuation was much more nearly sinusoidal with an amplitude of 2.5 f.p.s.

The next part of the investigation of configuration AU was the determination of the extent to which the injected air penetrated laterally and upstream into the test section. The penetration distance indicated the amount of usable test section lost since it would be undesriable to mount models in a region where they would be directly influenced by the injector air.

Accordingly, the hot wire was moved to a position nearly (1.0 inch off) in line with an injector nozzle and moved transversely and axially to determine the limits of the injected air. That the hot wire detected the pressure of the injected air can be seen from the data presented in Figure 20; the hot wire probe was located at Station 24. Figure 18 can be used for comparison; there the probe was at Station 24 but on the tunnel centerline.

Figure 21 presents the results of moving the probe 2 inches off the injector centerline at Station 24. Hot wire signals indicated that only at the lowest frequency was injector air detected. Therefore it was concluded that, for the injector pressures used (18 - 25 psia) injector air was confined to a cylinder, centered on the injector centerline, having a diameter roughly twice the injector diameter. Other tests indicated that this cylinder extended to the vicinity of Station 22 or about 10 nozzle diameters upstream of the nozzle exit. Therefore, since the nozzle exit was at Station 42 this nozzle configuration produced injected air which directly affected about 50 percent of the available test section length. This distance could be reduced by using a larger number of smaller diameter nozzles, a factor which is well to consider in designing the next system.

The frequency response characteristic for this configuration is shown in Figure 22 and at low injector pressures was similar to that obtained with configuration A. However, by comparing the data of Figure 22 with that of Figure 16B for configuration A, it is seen that the influence of injector pressure was much greater with AU than with A. A possible explanation of this is the interaction between the injected air and the injectors, an effect which would not be present in the A configuration.

Based on the available data it is concluded that the frequency response characteristic was largely determined by the tunnel circuit for configuration A but that for configuration AU the injector system characteristics were dominant. This influence of the injector system could probably be substantially reduced by installing the modulating valves at the injector nozzle entrance and eliminating most of the injector pneumatic system. If this were done it is likely that the response characteristic would be determined by the tunnel circuit.

While there was no doubt some acoustic transmission of disturbances there was nothing in the present data to suggest that this was a major contributor to the phenomena noted.

It was stated earlier that configuration AU was more efficient than configuration A in terms of the fluctuation amplitude induced for a given injector pressure. The data supporting this conclusion is presented in Figure 23 for injector pressure pulses of 6 psi. Comparable results were obtained for other injector pressure levels. It can be seen that AU was roughly 2-3 times as efficient as A. This is important since it affects directly the size of the air supply system needed for the injectors, and, in large wind tunnels, this will be a major cost item. Therefore in the remainder of this study, no downstream facing nozzle systems will be investigated.

Using a crossed wire probe with wires at 45^{o} from the tunnel centerline measurements of the transverse velocity components were made. Preliminary results indicate that at Station 24 the transverse component was approximately 1.5 f.p.s. when the longitudinal induced fluctuation was 6.0 f.p.s. at a frequency of 55 c.p.s. This transverse component was large since the flow at station 24 was downstream of the upstream end of the portion of the test section affected by injected air. Additional data is required to adequately define the "purity" of the longitudinal gusts generated.

Preliminary Results of Two-Dimensional Gust Production

The results presented earlier in this report were related to the production of longitudinal, i.e., one dimensional, gusts. Near the end of the period covered by this report initial attempts were made to induce two-dimensional gusts, i.e., gusts involving fluctuation in both longitudinal and transverse (horizontal) velocity components.

This was done by pulsing the two left hand injectors (see Figure 9) out of phase with the two right hand injectors. Preliminary results are presented in Figure 24 and indicate that transverse components at Station 18 in the range from 8.11 f.p.s. to 2.04 f.p.s. were induced at frequencies up to 65 c.p.s. Other measurements at Stations 12 and 24 indicate that the magnitude of the transverse component decreased as the probe moved upstream.

Additional studies of the 2-dimensional gust induction will be completed. Of special interest will be off-centerline measurements which will indicate wall attenuation effects.

Conclusions

Based on the tests conducted thus far in the research program the following conclusions were made:

1. The air injection technique can be used to induce longitudinal (one-dimensional) gusts in a wind tunnel. Preliminary results indicate that two-dimensional gusts can also be produced.
2. Gust frequencies of well over 50 c.p.s. were achieved with amplitudes of approximately 5.5 f.p.s. on a 83.0 f.p.s. stream. At lower frequencies long individual gust amplitudes up to 21 f.p.s. were induced. Gusts were also induced in a 97.8 f.p.s. stream.
3. The high frequency turbulence level in the stream was not materially affected by the addition of injector air.
4. The gust amplitudes varied with frequency for a constant injector pressure. The data indicate that transmission of the gusts around the circuit was a dominant factor with configuration A, while injector system characteristics were dominant for Configuration AU.

5. The gusts generated at frequencies up to 35 c.p.s. were reasonably sinusoidal but at higher frequencies some "beating" occurred, particularly for configuration AU.
6. Upstream-facing injectors were much more efficient, in terms of gust velocity induced for a given injector pressure, than downstream-facing injectors.
7. Injected air extended approximately 10 nozzle diameters upstream from the injector nozzle exit plane.

References

1. Pankhurst and Holder, "Wind Tunnel Technique".

2. Anonymous, "Model HWB Hot Wire Anemometer; Theory and Instructions," Flow Corporation, Cambridge, Massachusetts, 1955.

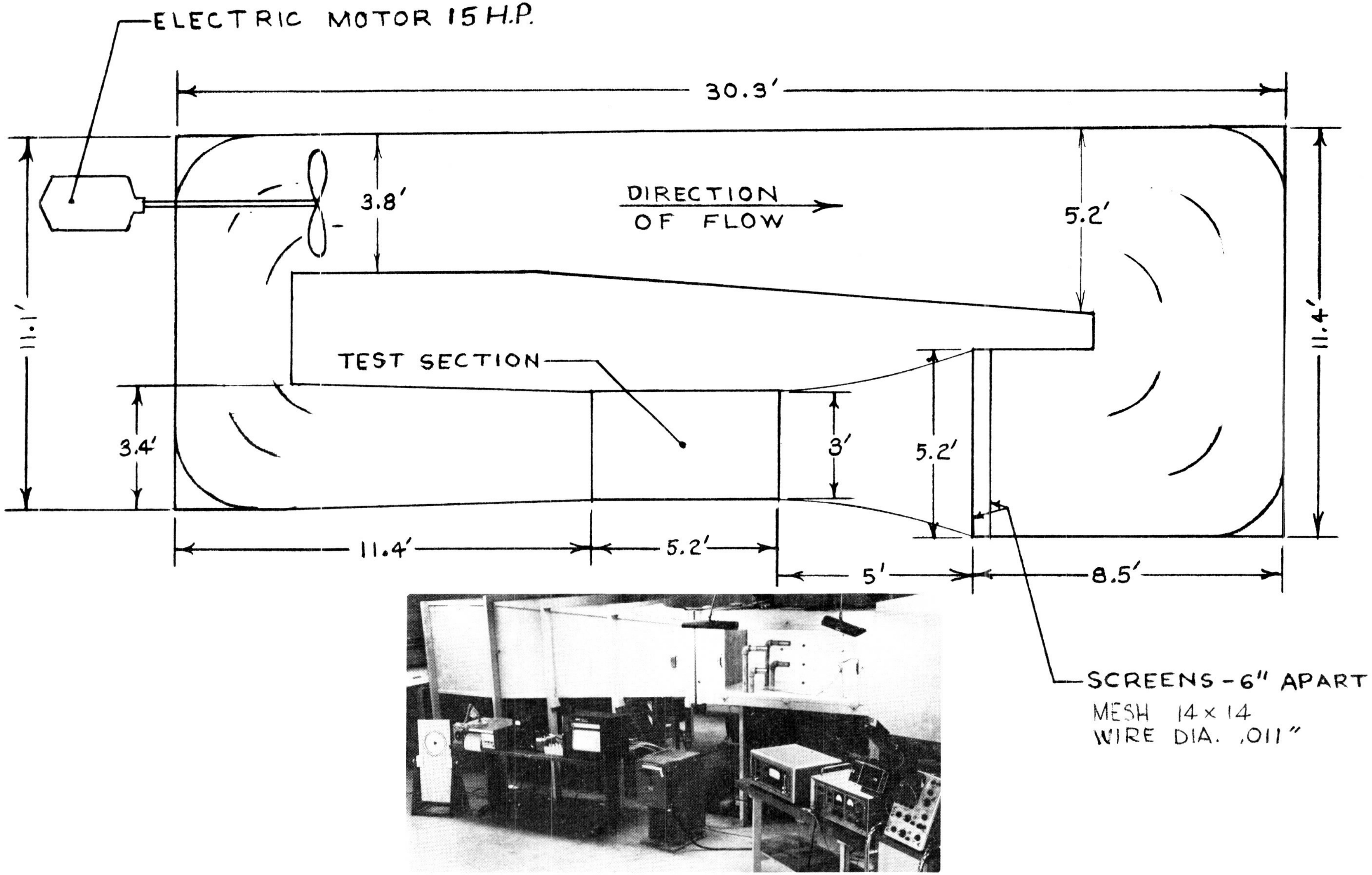


Figure 1-Two Foot x Three Foot Low Speed Wind Tunnel

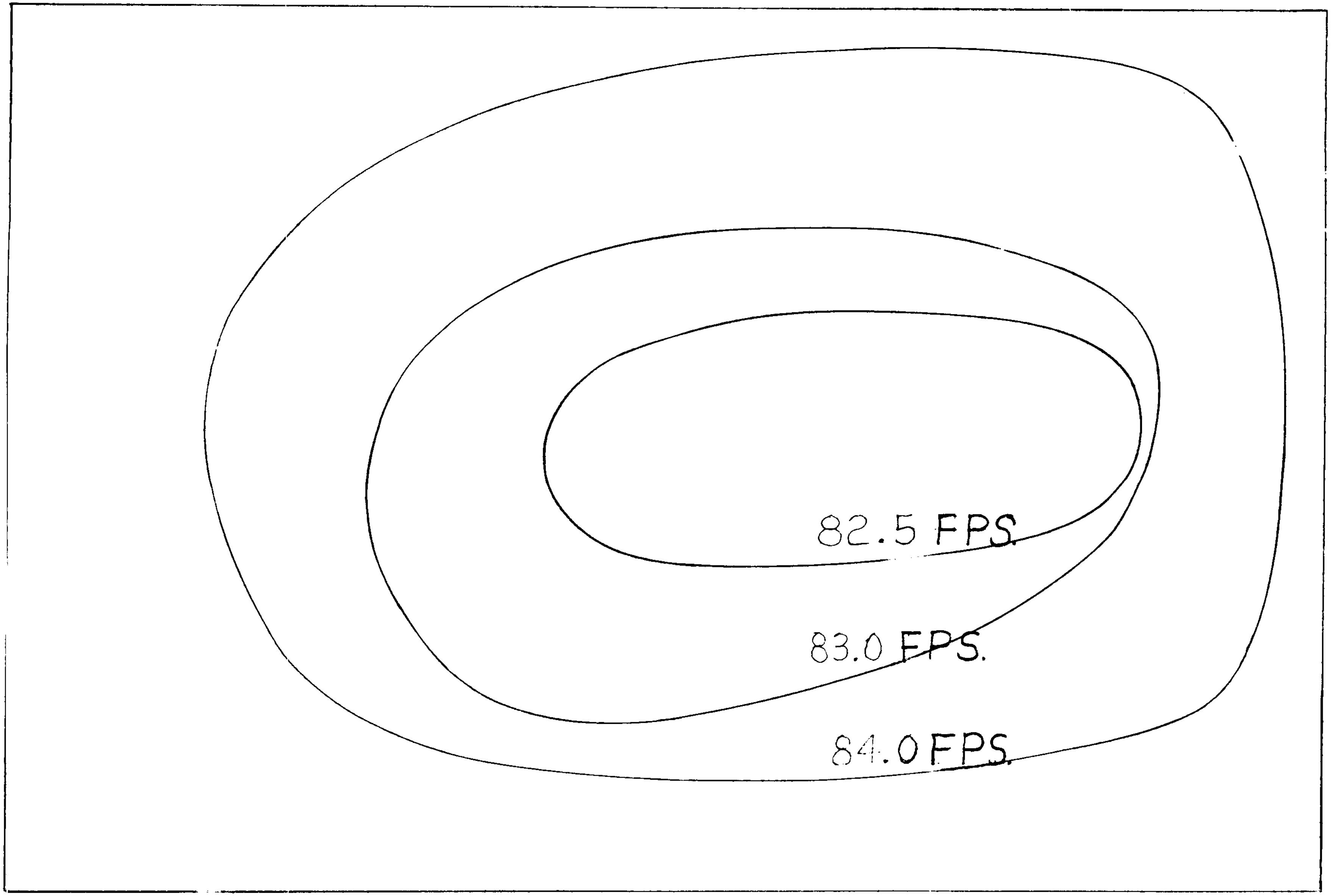


Figure 2-Velocity Contours, Station 12

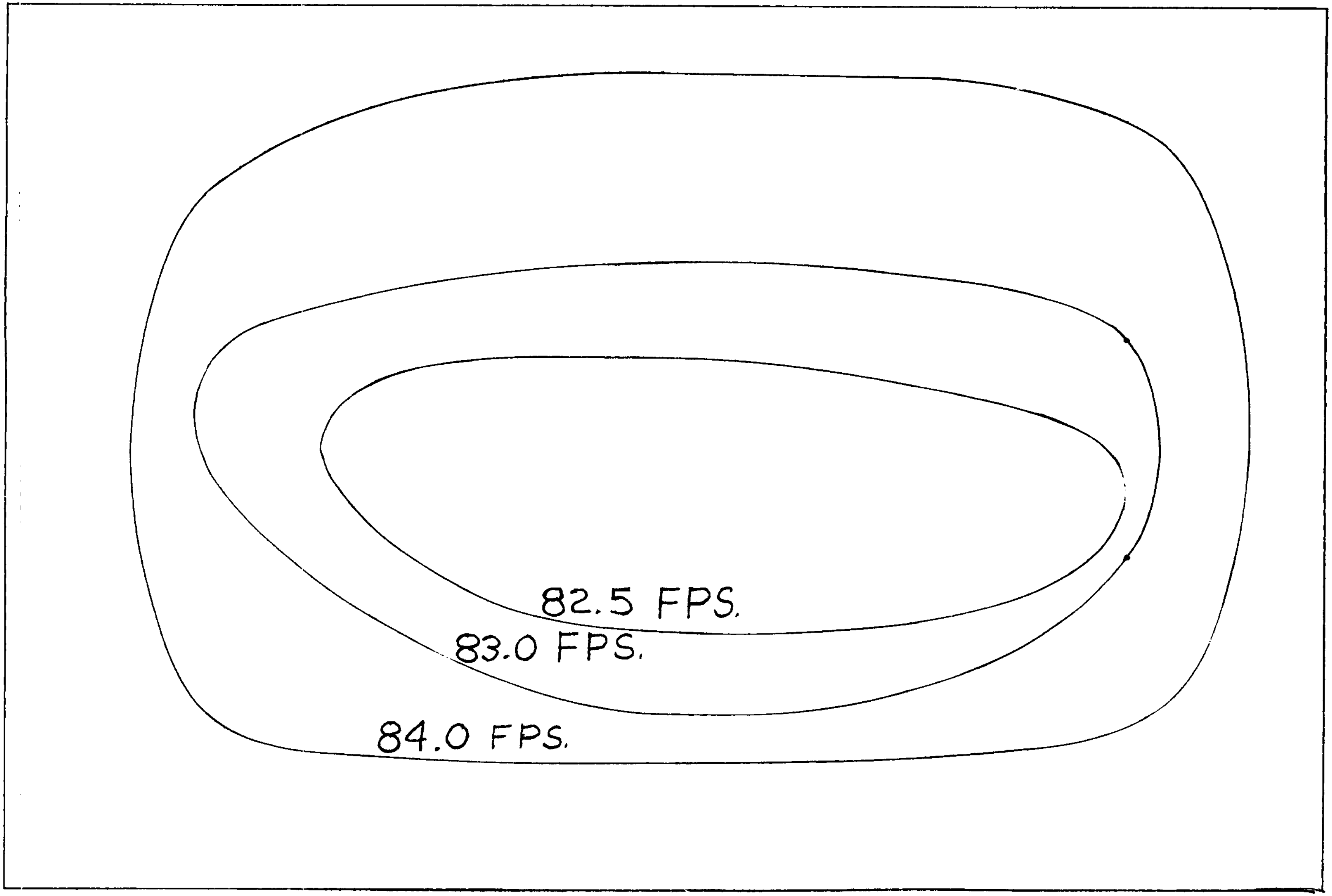


Figure 3-Velocity Contours, Station 24

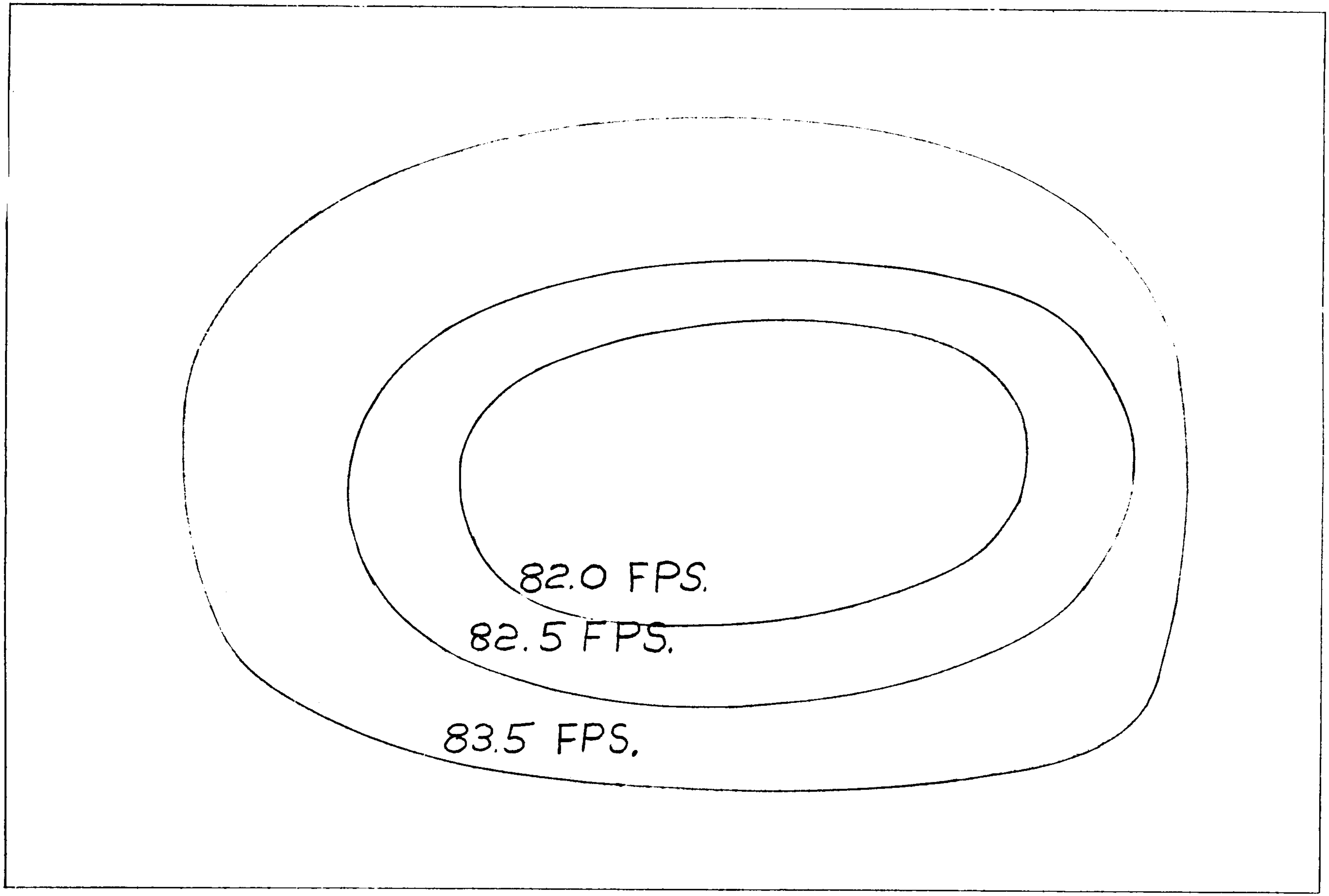


Figure 4-Velocity Contours, Station 36

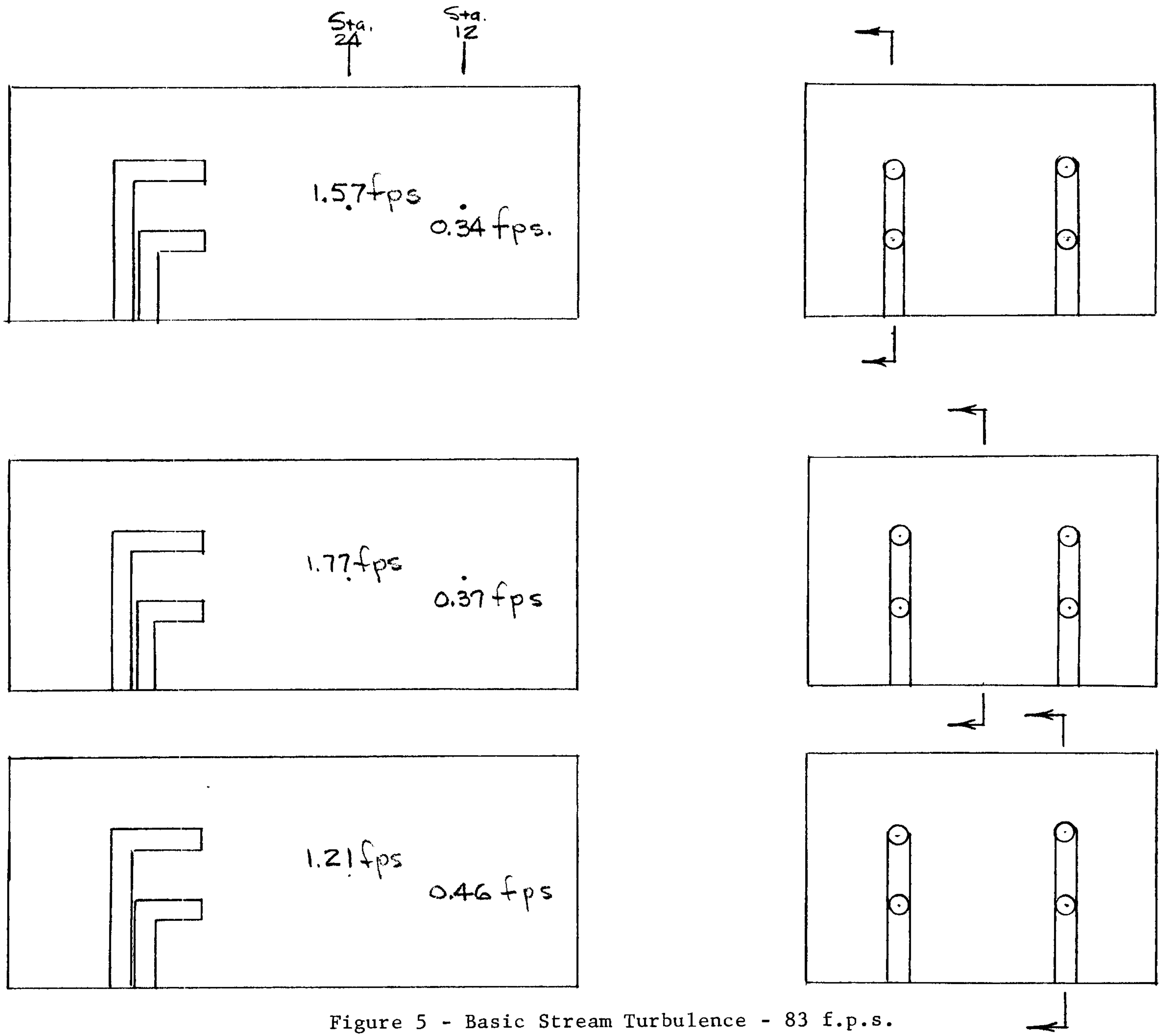


Figure 5 - Basic Stream Turbulence - 83 f.p.s.

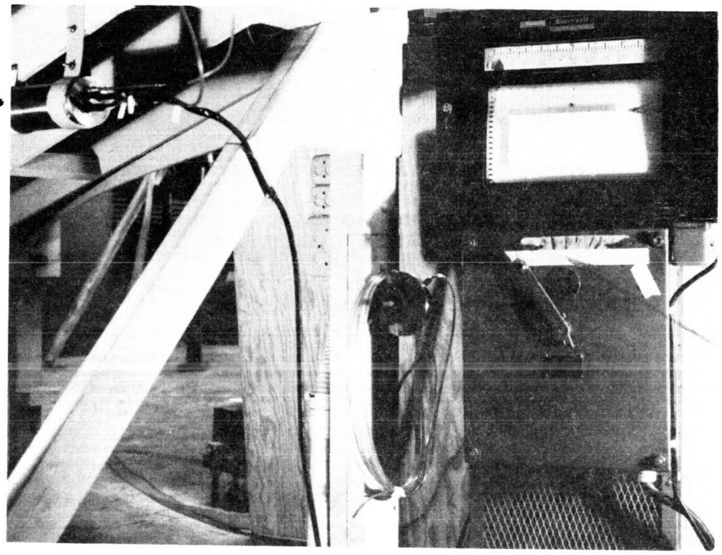
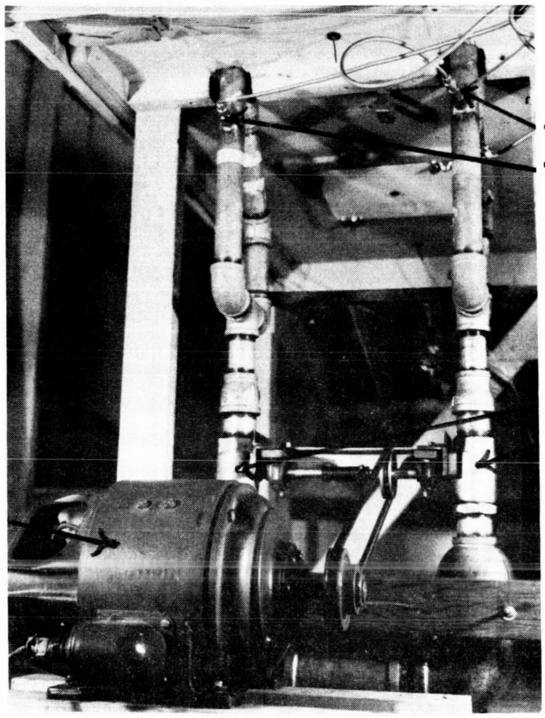
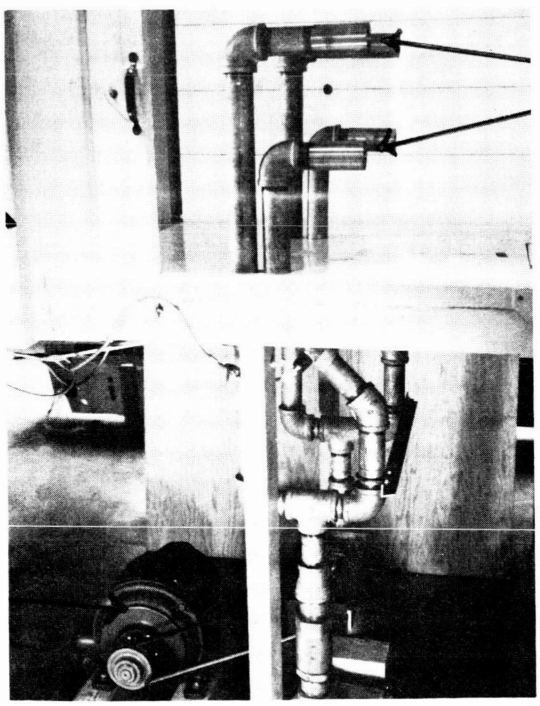


Figure 6 - Tunnel Speed Control System



Rear view
Modulating valve system



Side view
Configuration AU

Figure 7-Photographs of the Modulation Valve System

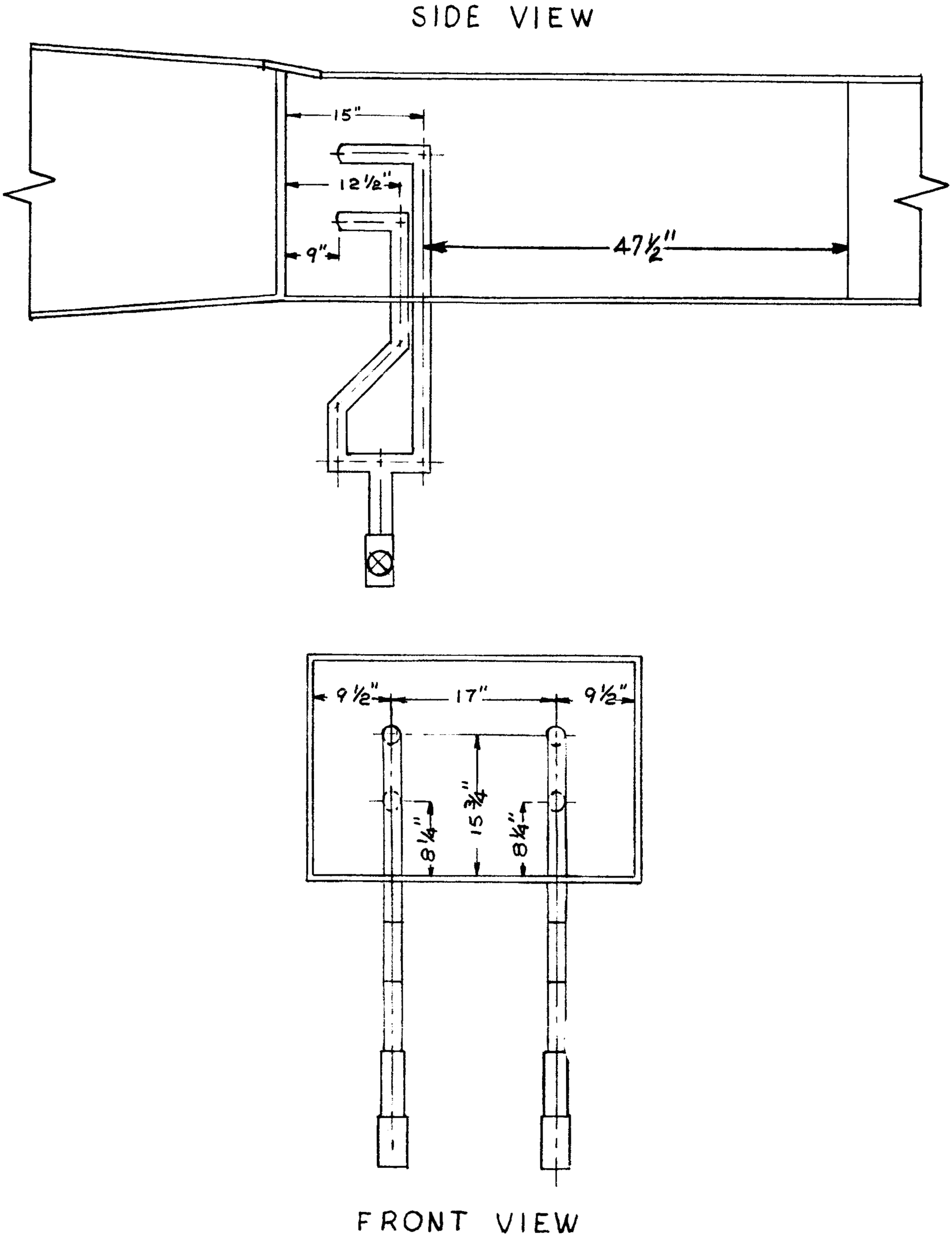


Figure 8-Injector Configuration "A"

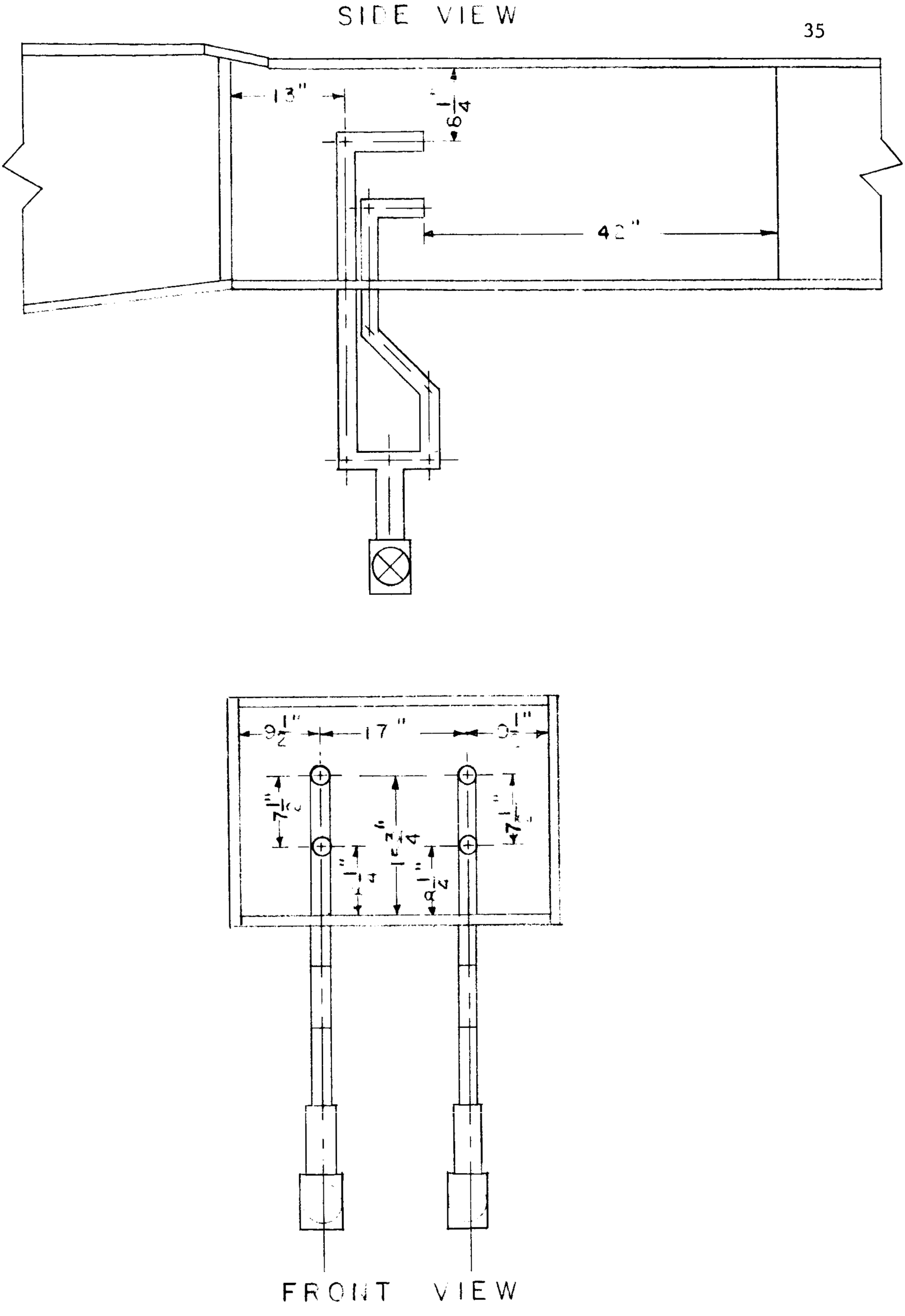


Figure 9-Injector Configuration "Au"

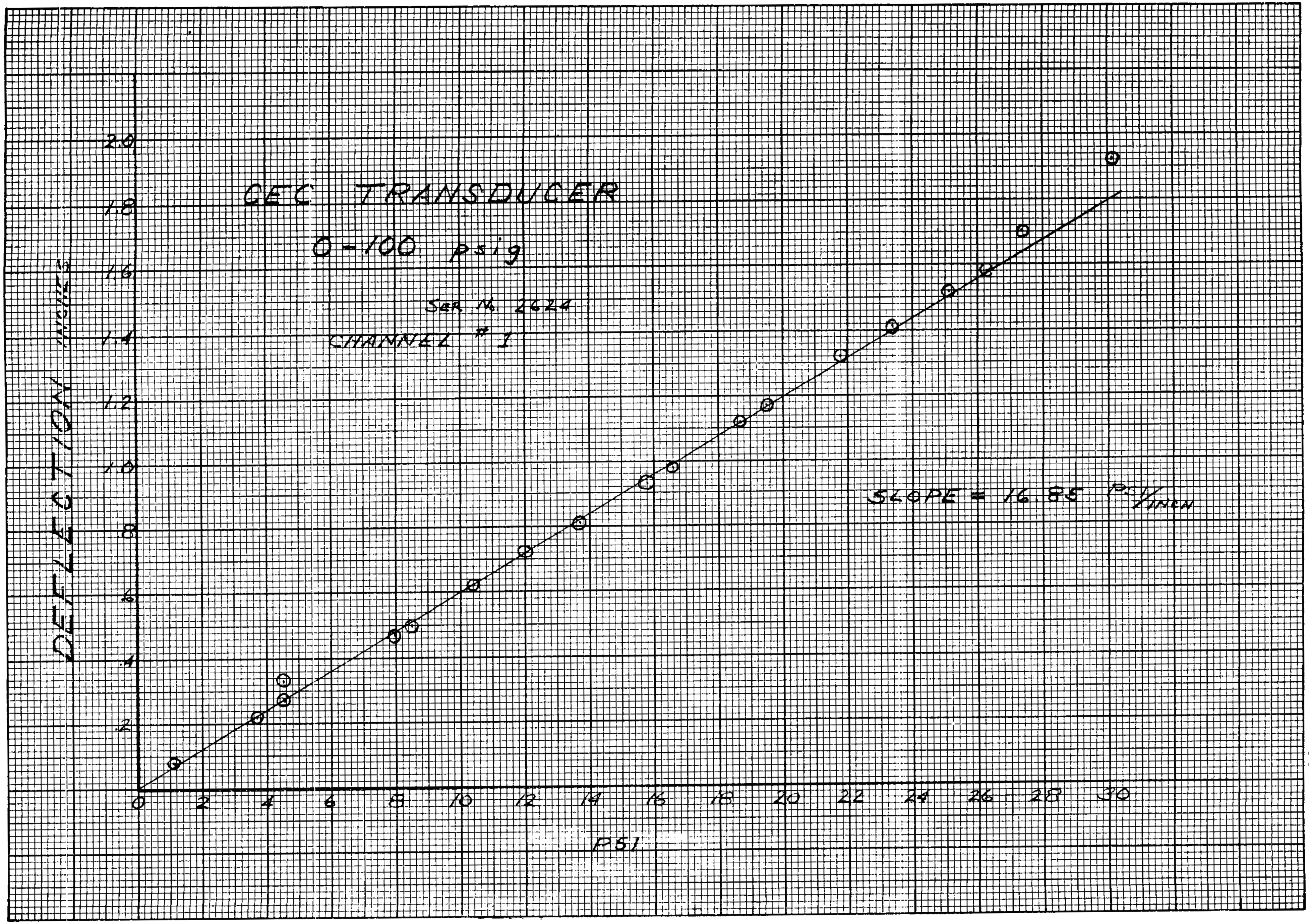


Figure 10-Calibration of Injector Transducer

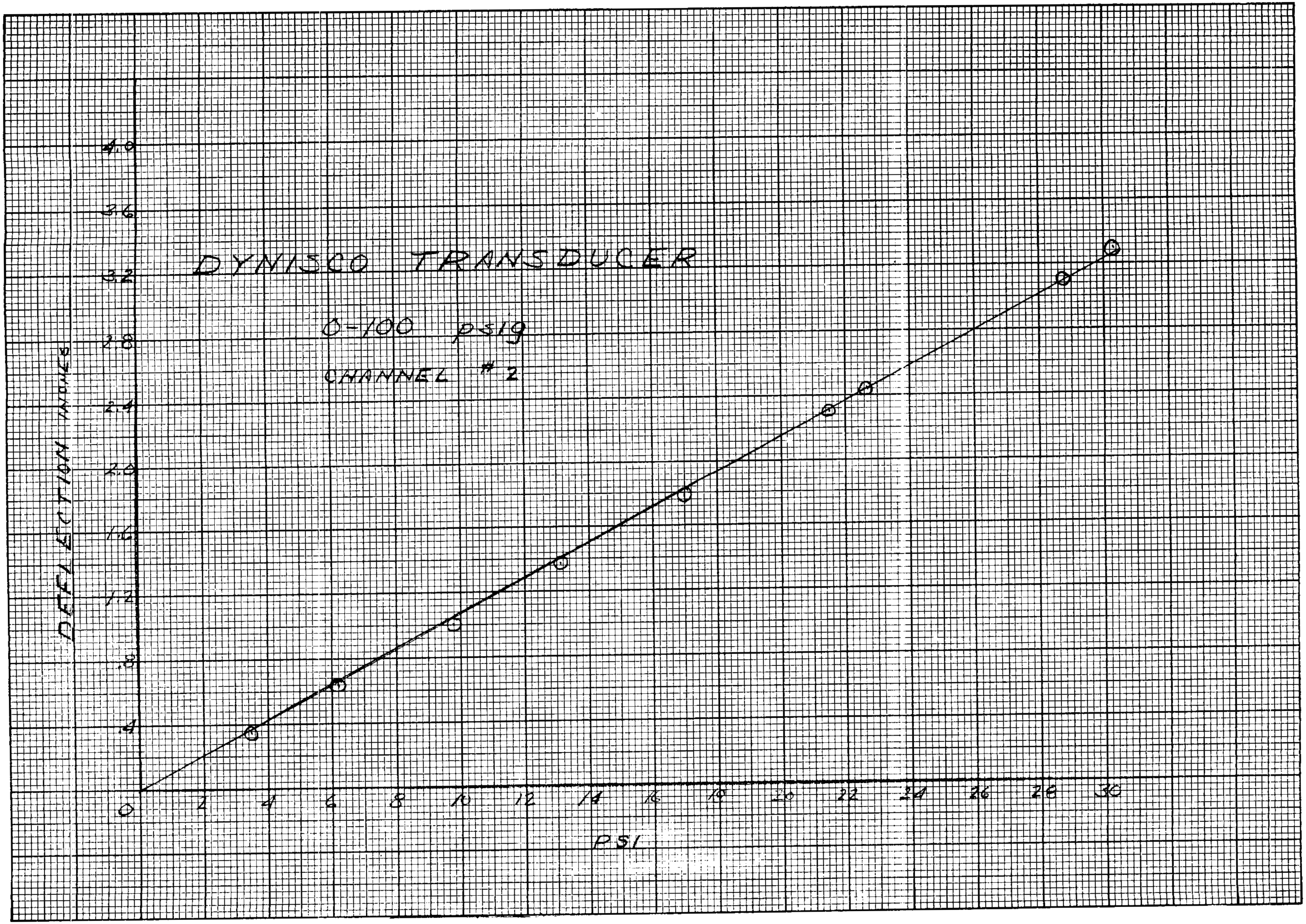


Figure 11-Calibration of Injector Transducer

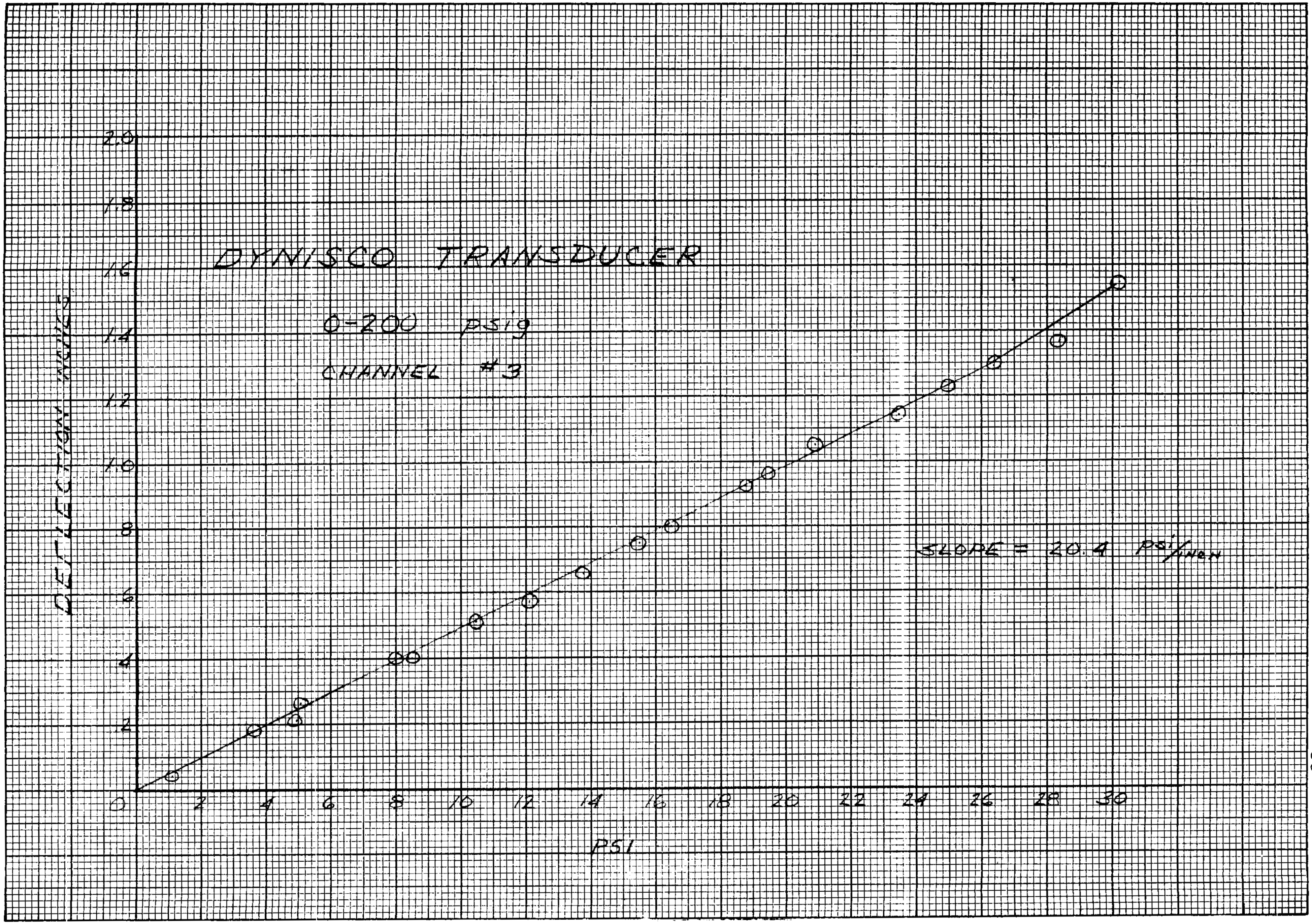


Figure 12-Calibration of Injector Transducer

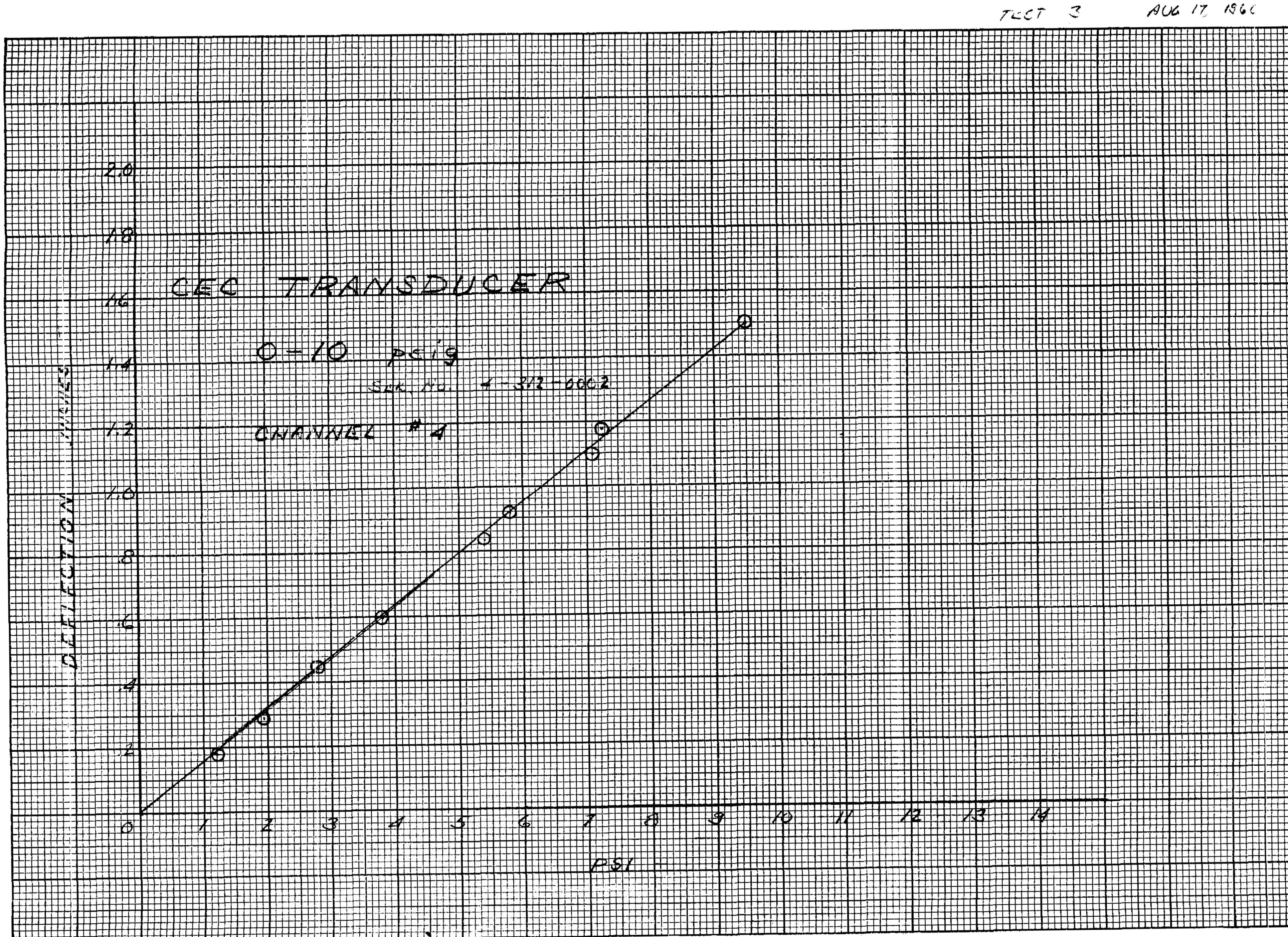


Figure 13-Calibration of Injector Transducer

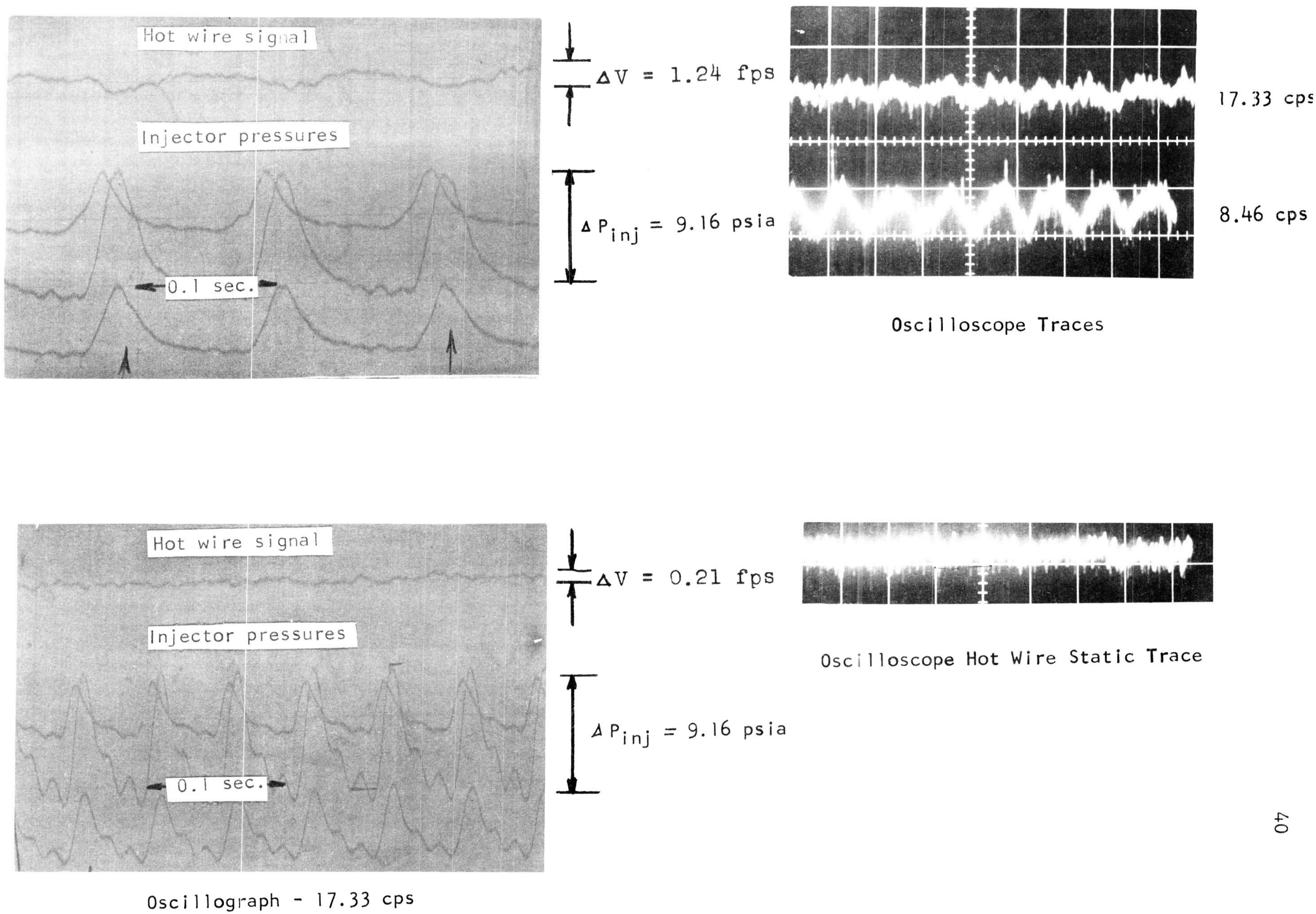
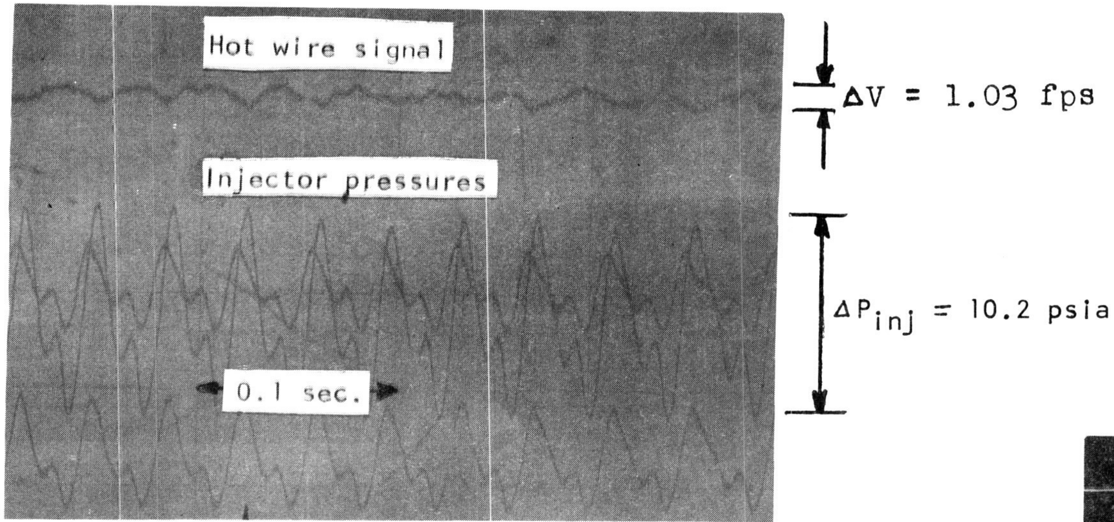
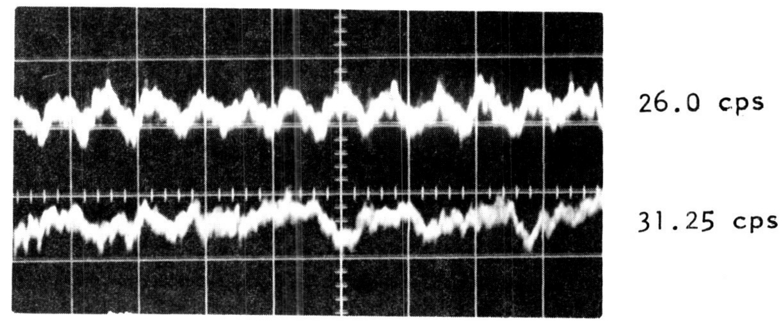


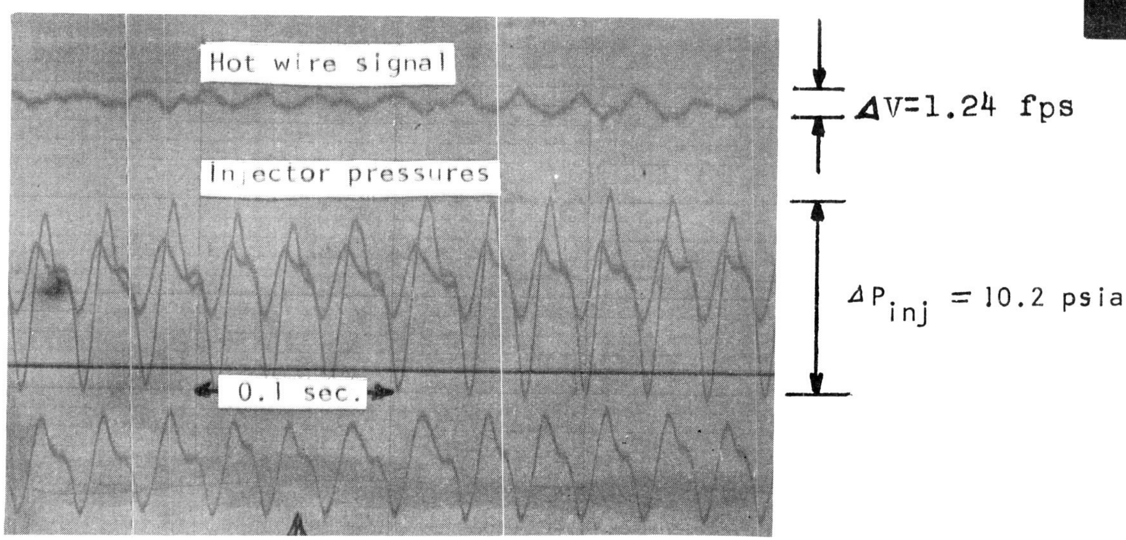
Figure 14 A - Test Results, Conf. A, 70 fps



Oscillograph - 26.0 cps

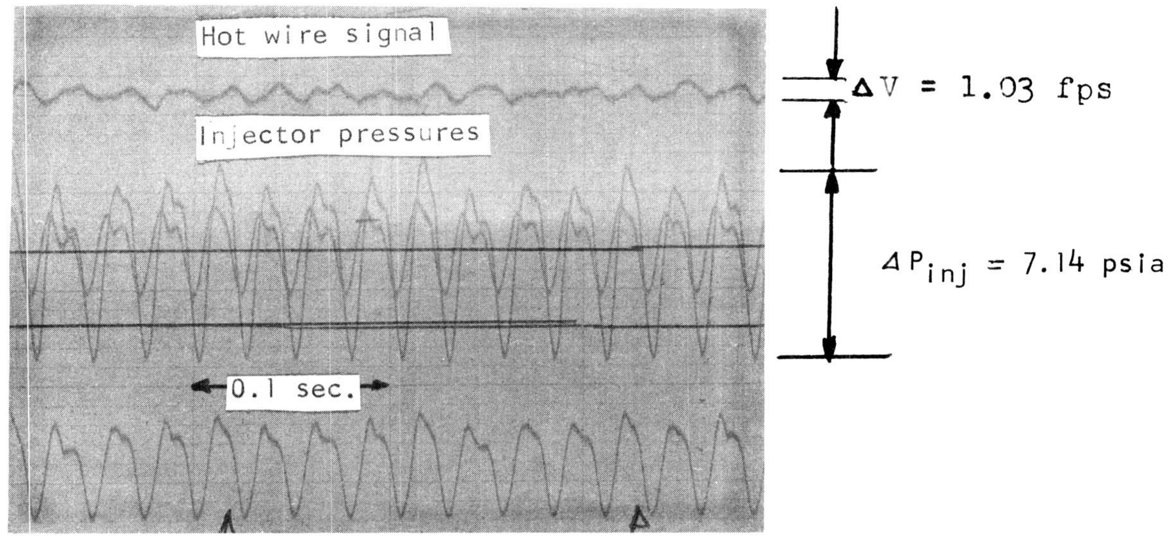


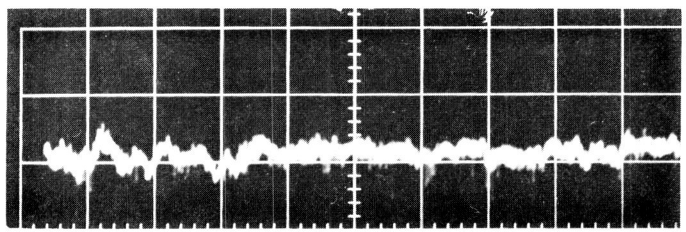
Oscilloscope traces



Oscillograph - 31.25 cps

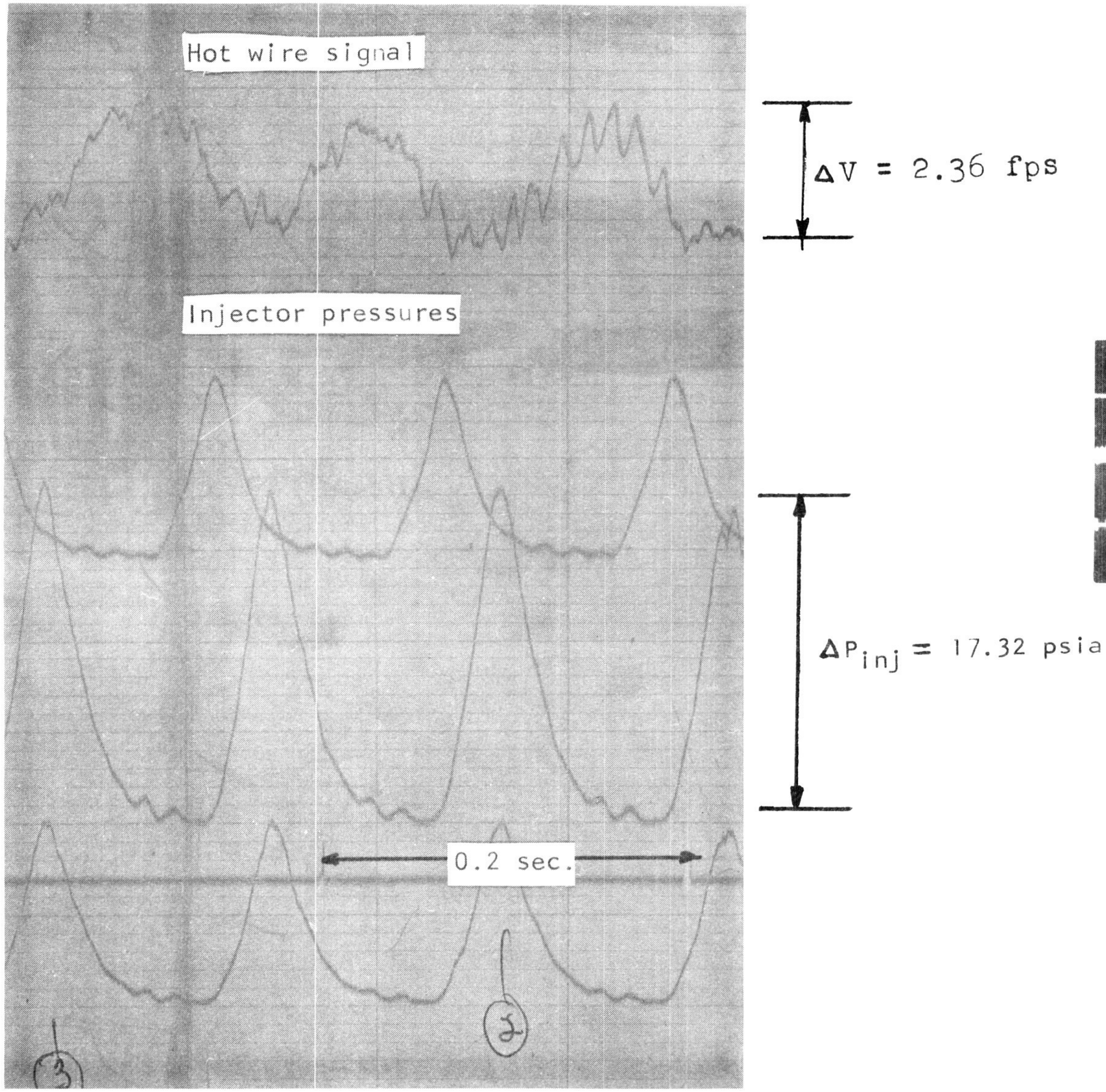
Figure 14 B - Test Results, Conf. A, 70 fps



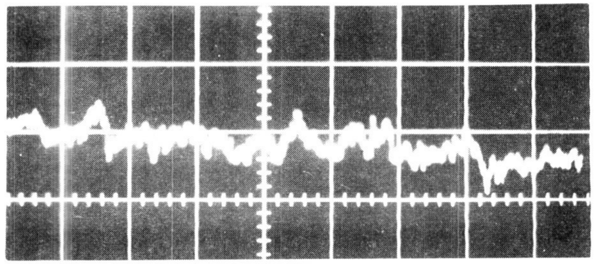


Oscilloscope trace 38 cps

Figure 14 C - Test Results, Conf. A, 70 fps

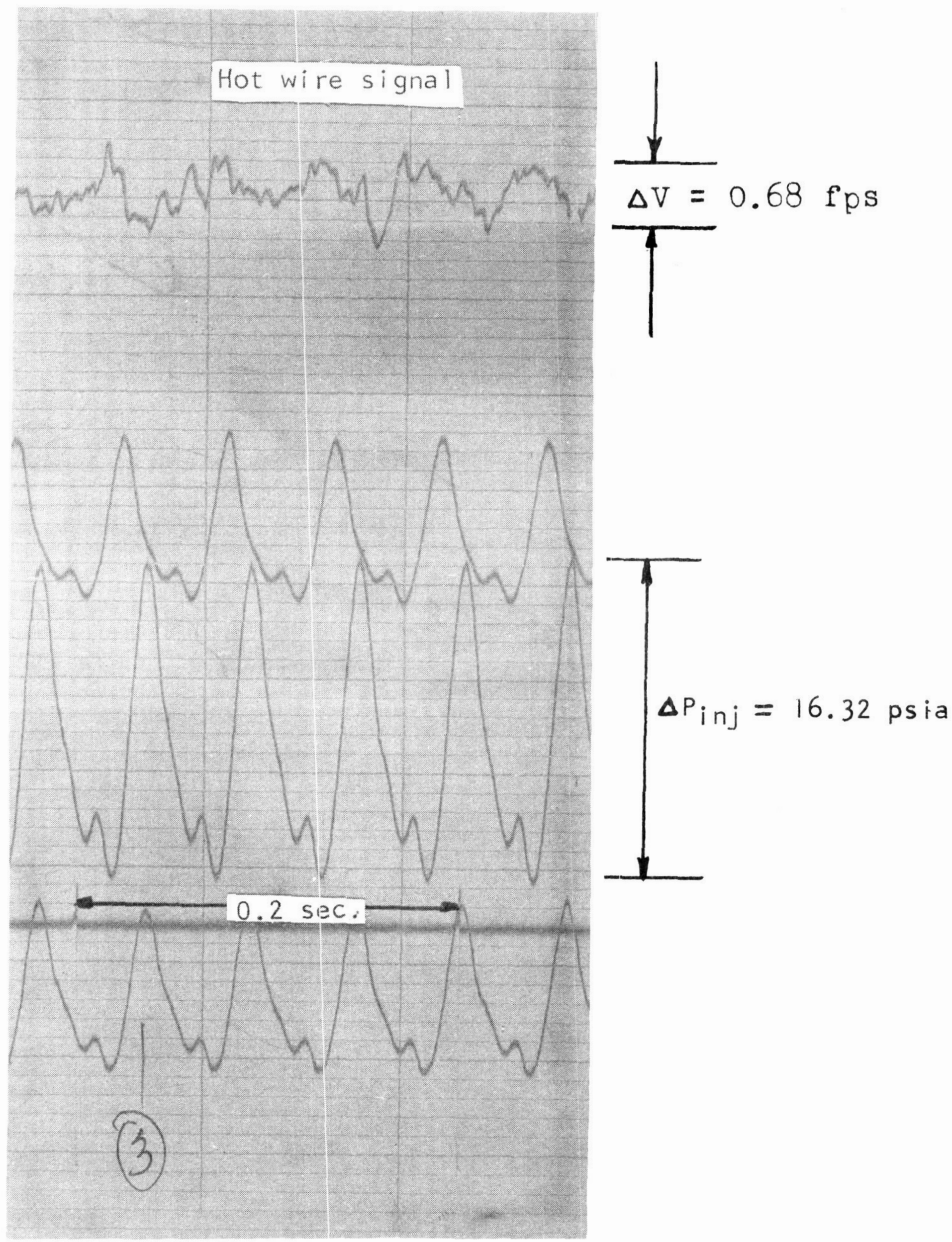


Oscillograph - 8.57 cps

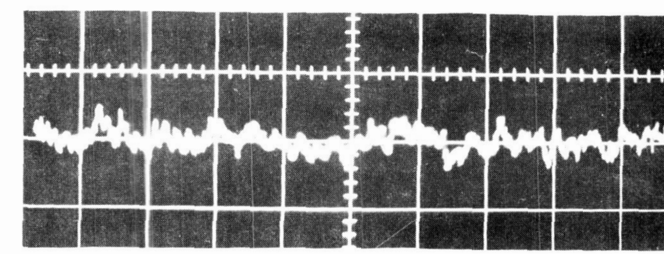


Oscilloscope trace 8.57 cps

Figure 15 A - Test Results, Conf. A, 97.8 fps

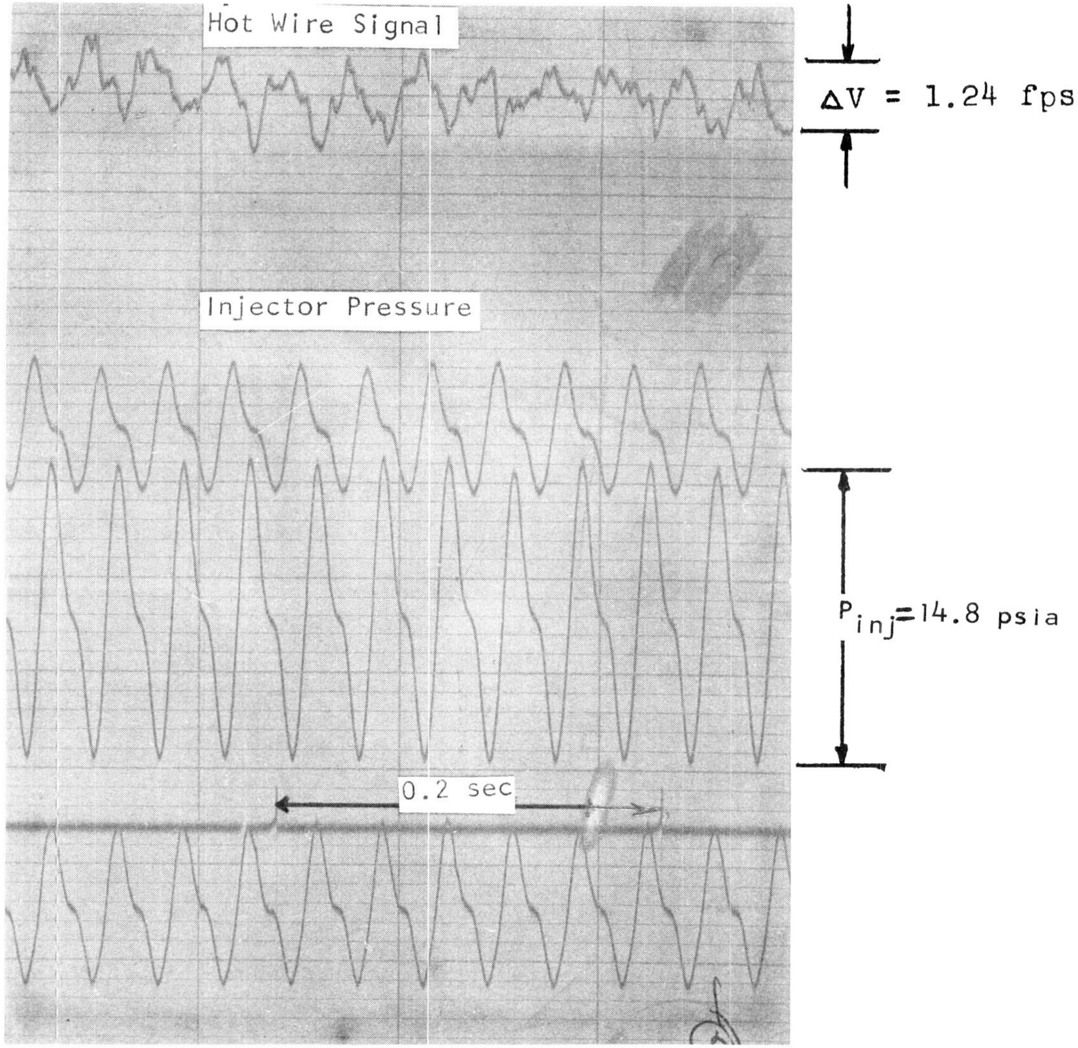


Oscillograph - 18.60 cps

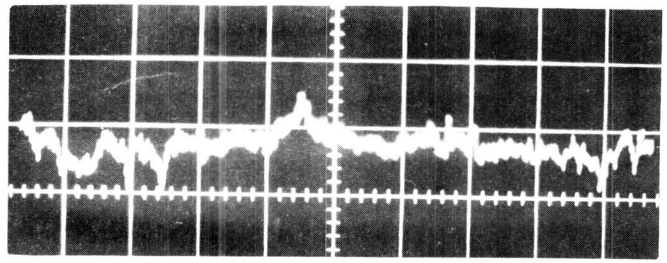


Oscilloscope trace 18.60 cps

Figure 15 B - Test Results, Conf. A, 97.8 fps

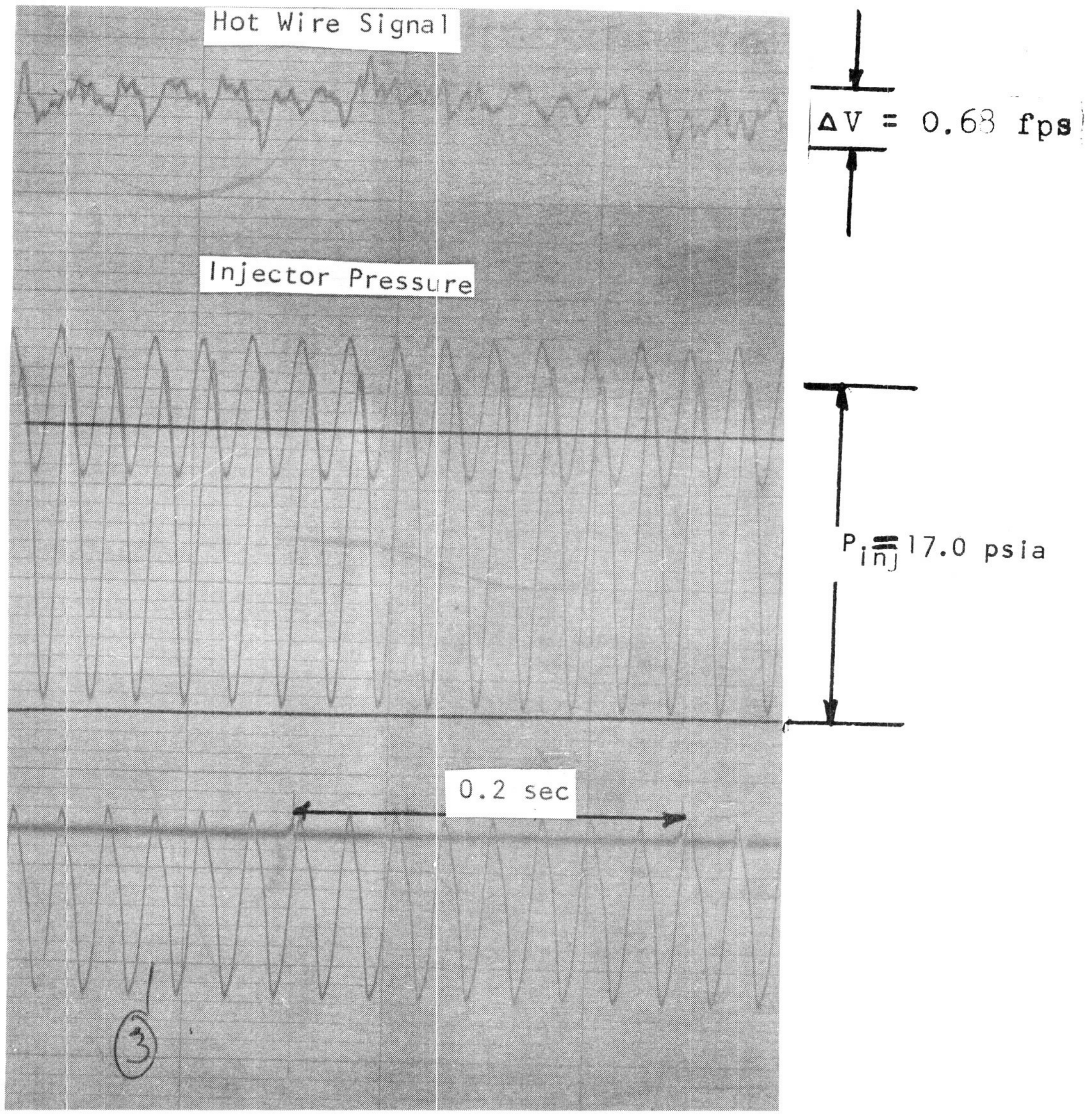


Oscillograph-30.0 cps

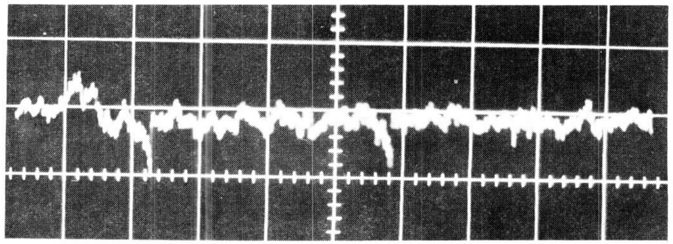


Oscilloscope Trace 30.0 cps

Figure 15C-Test Results, Config. A, 97.8 fps

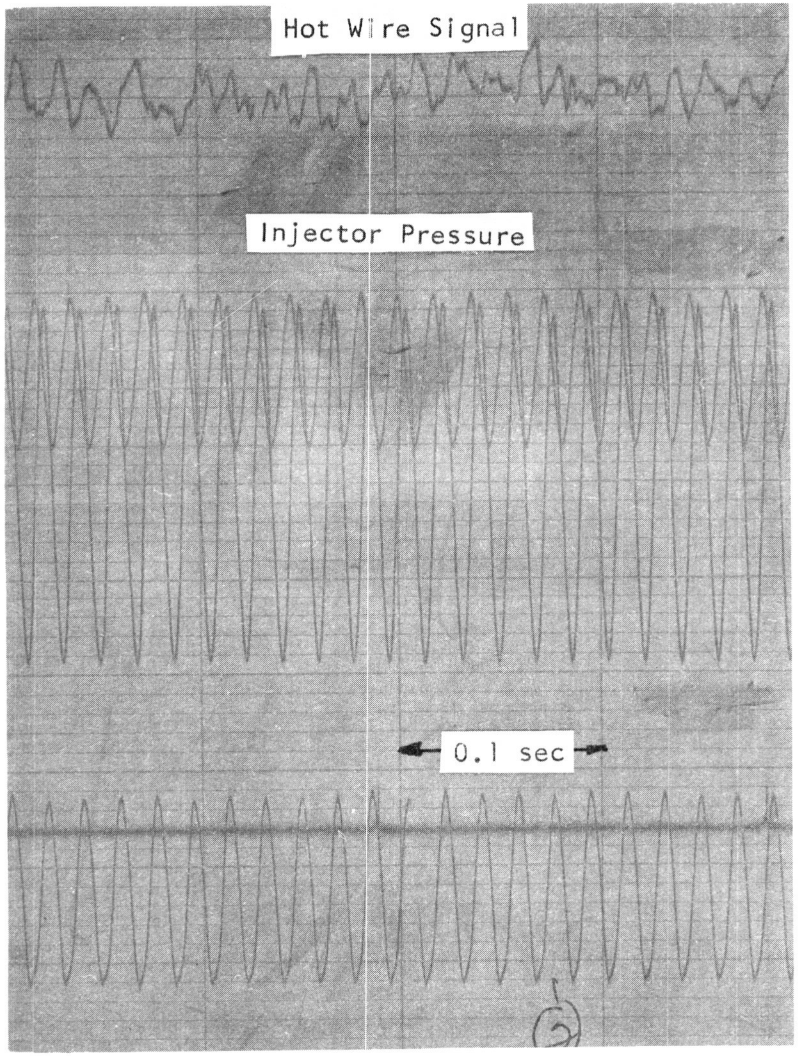


Oscillograph-42.3 cps



Oscilloscope Trace 42.3 cps

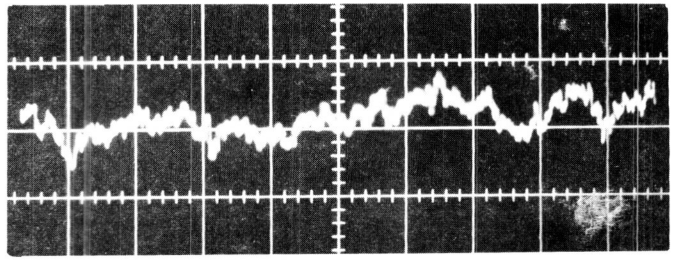
Figure 15D-Test Results, Config. A, 97.8 fps



$\Delta V = 1.01$ fps

$\Delta P_{inj} = 17.8$ psia

Oscillograph-55. cps



Oscilloscope 55 cps

Figure 15E-Test Results, Config. A, 97.8 fps

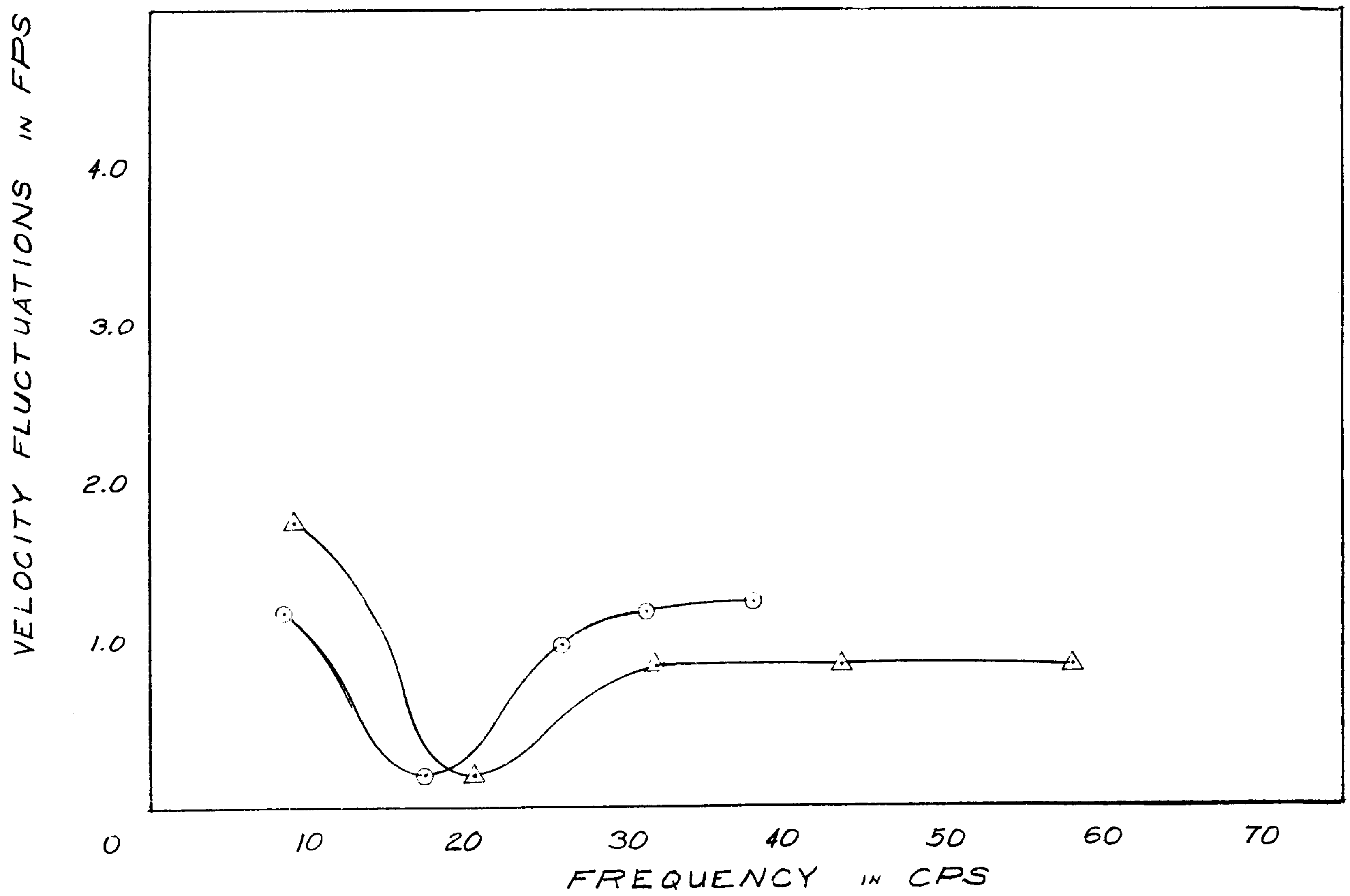


Figure 16 A - Frequency Response at Two Tunnel Velocities

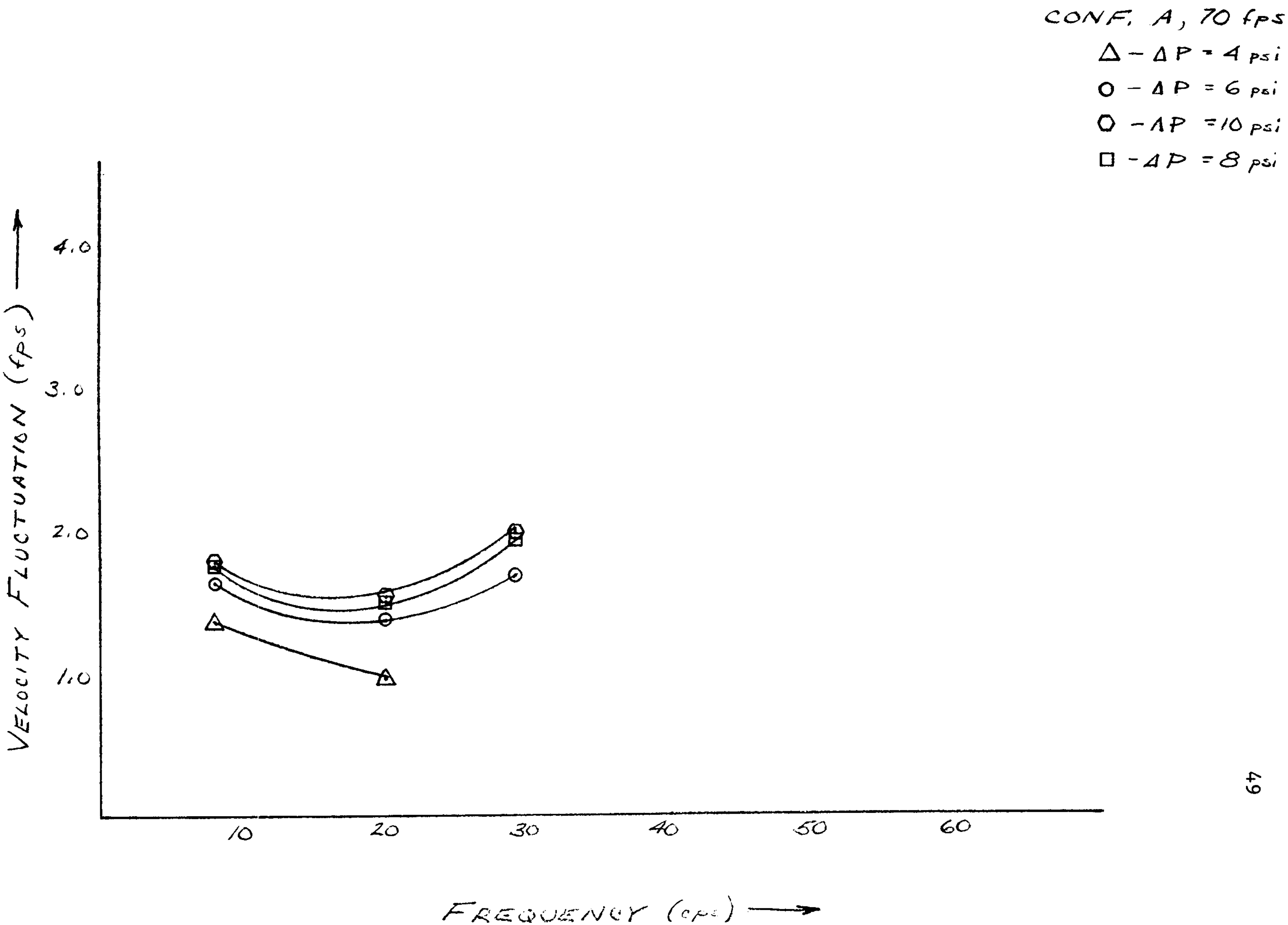


Figure 16 B - Frequency Response at Several Injector Pressures

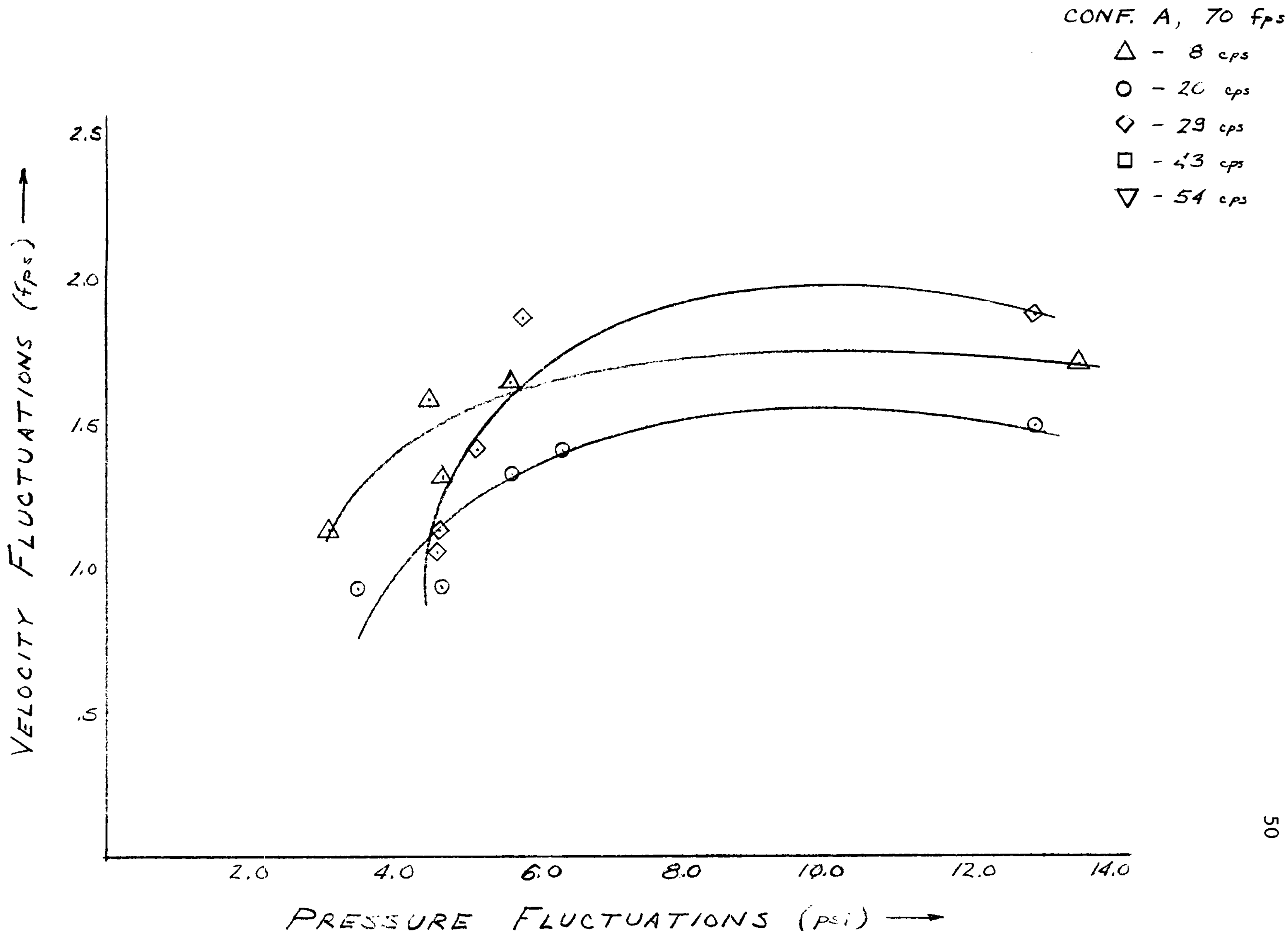
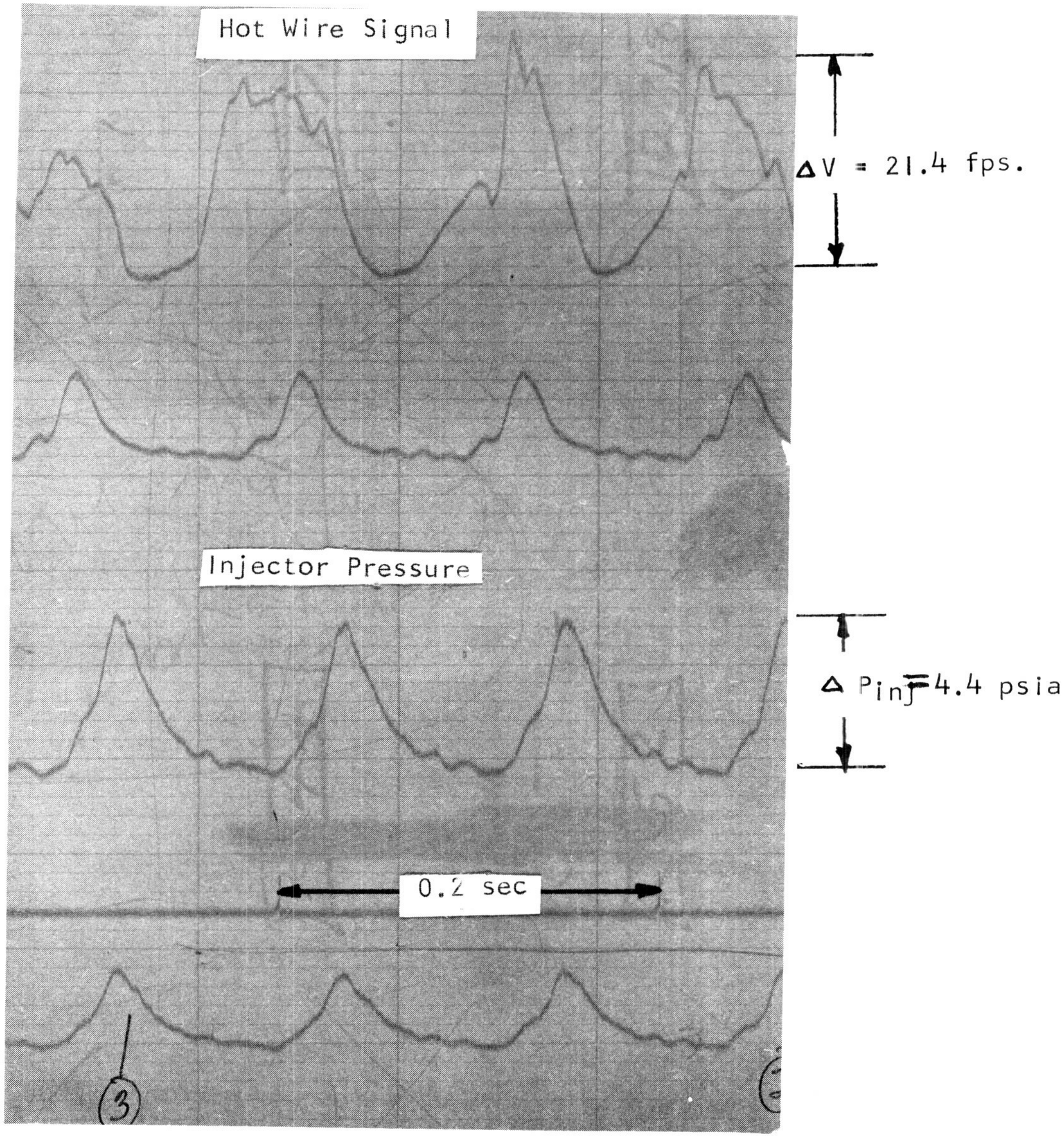
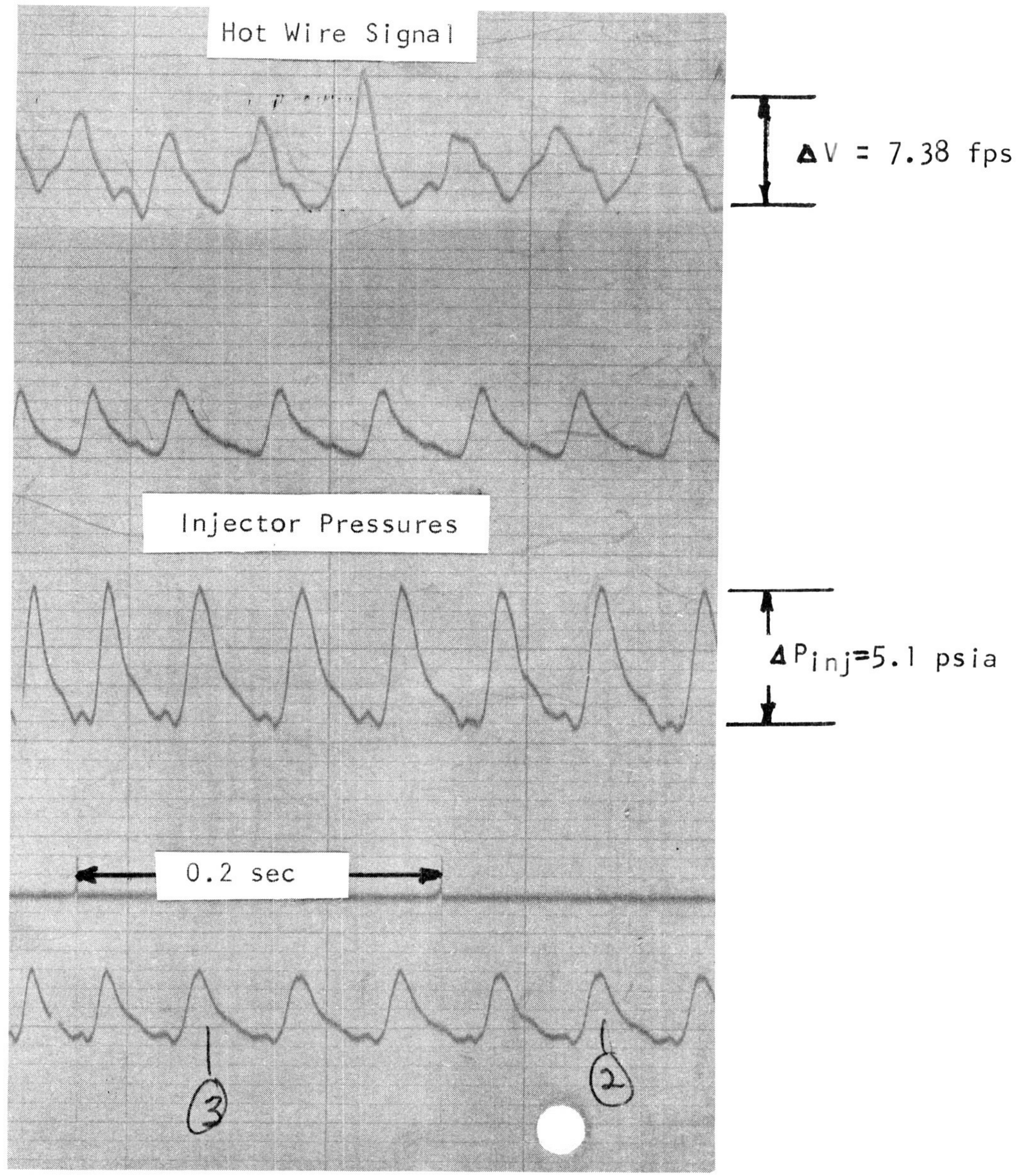


Figure 17 - Velocity Fluctuation versus Injecter Pressure Fluctuation



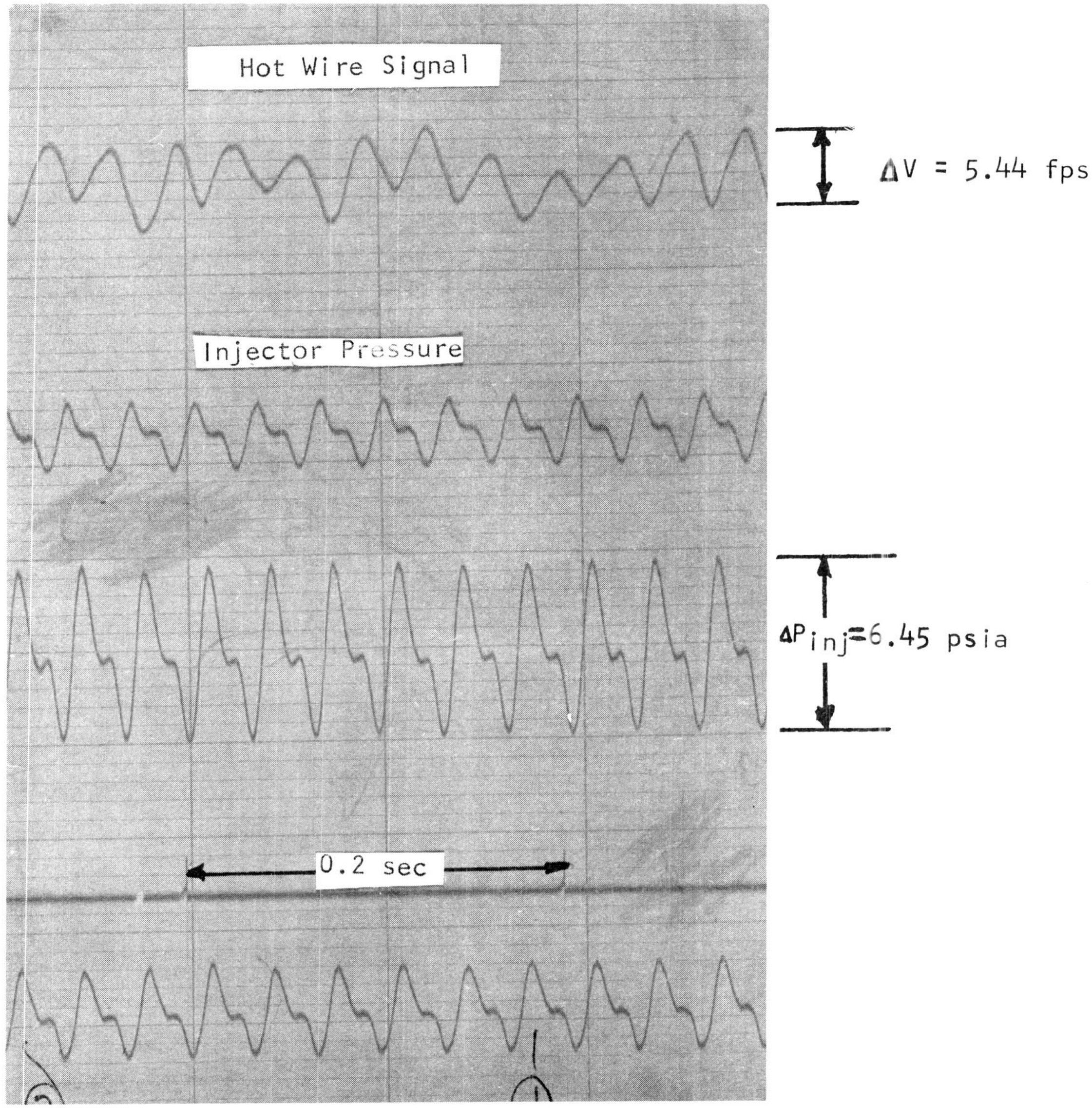
Oscillograph-8.6 cps

Figure 18-Test Results, Config. Au-83 fps



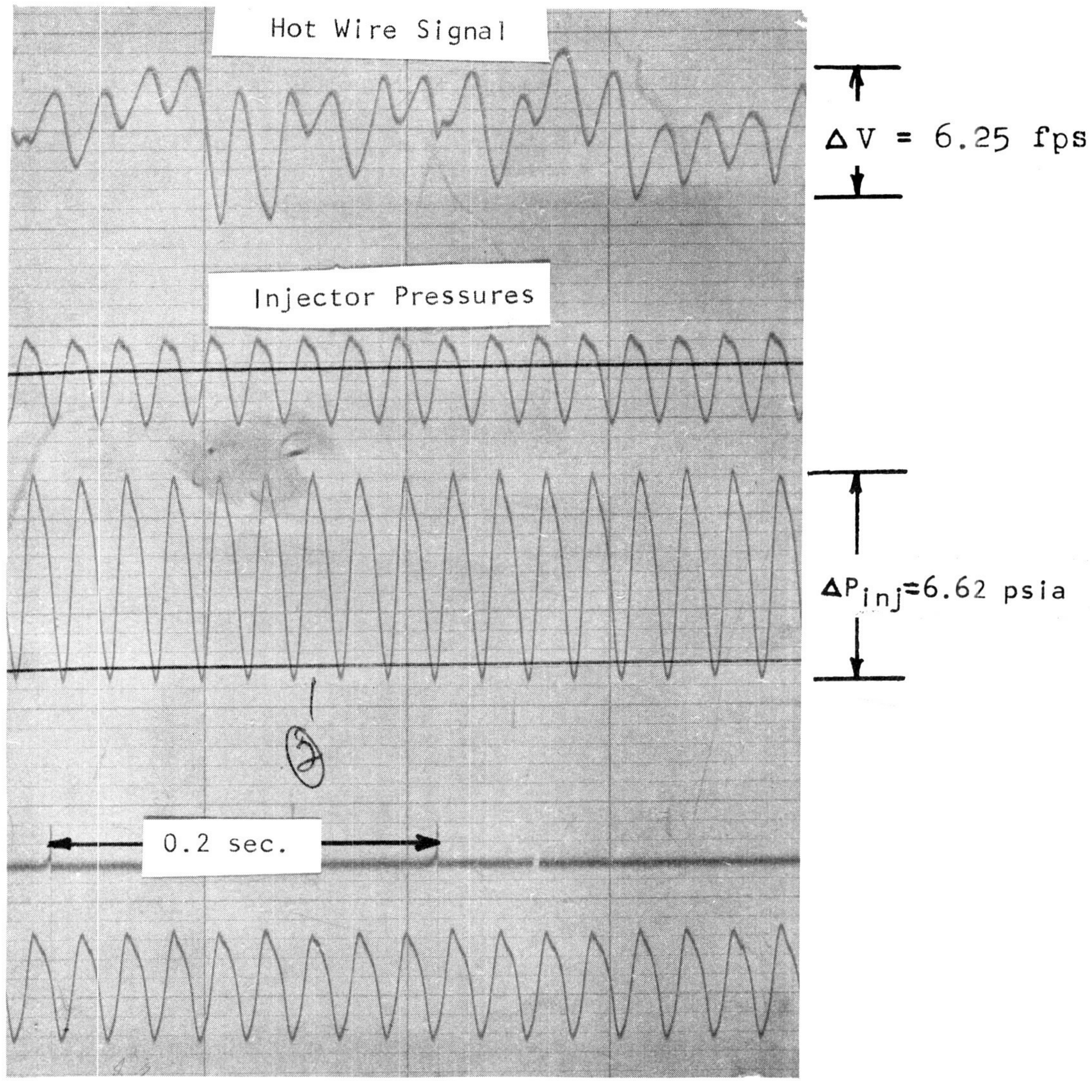
Oscillograph-19.0 cps

Figure 18B-Test Results, Config. Au-83 fps



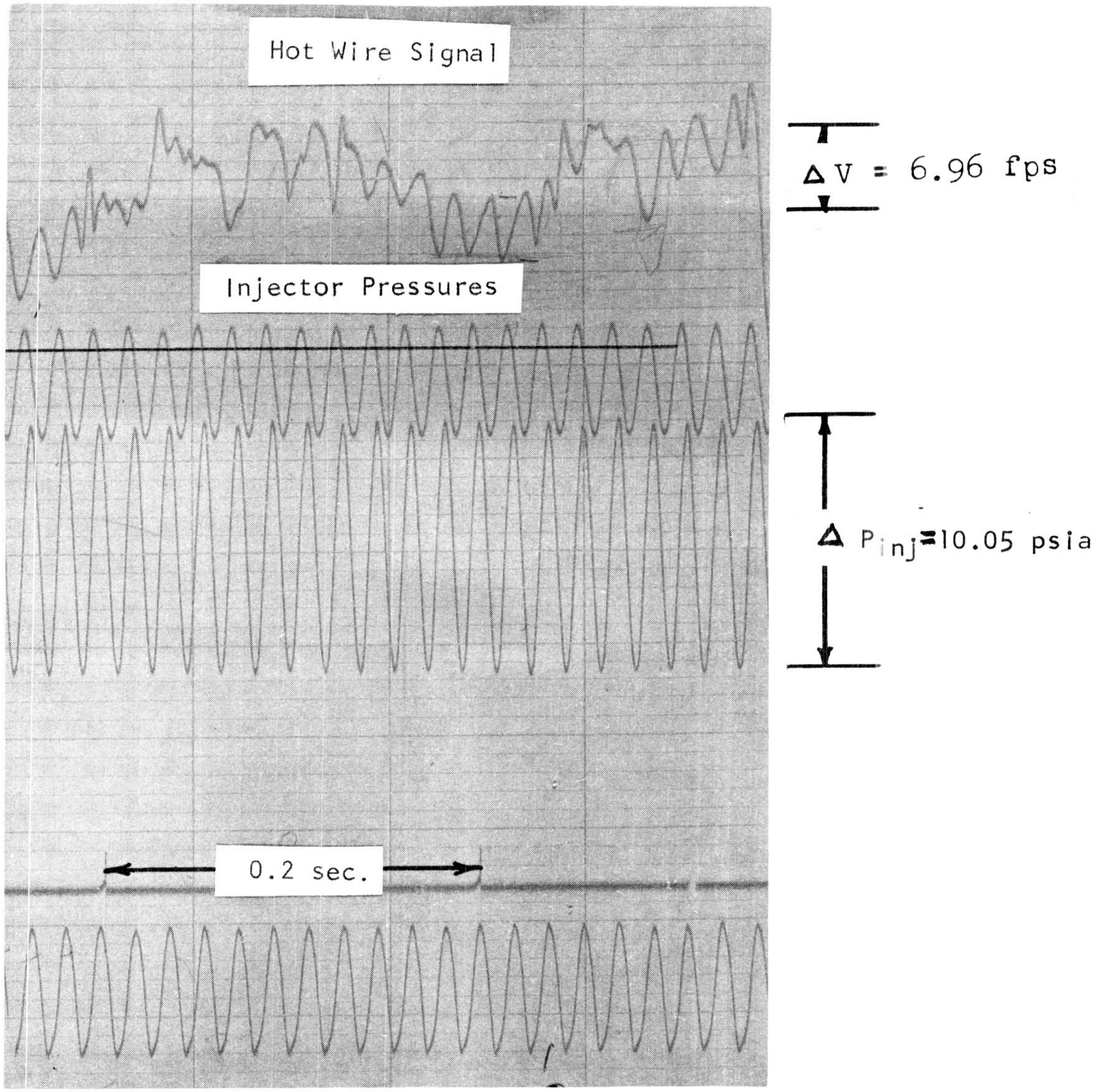
Oscillograph-34.5 cps

Figure 18C-Test Results, Config. Au-83 fps



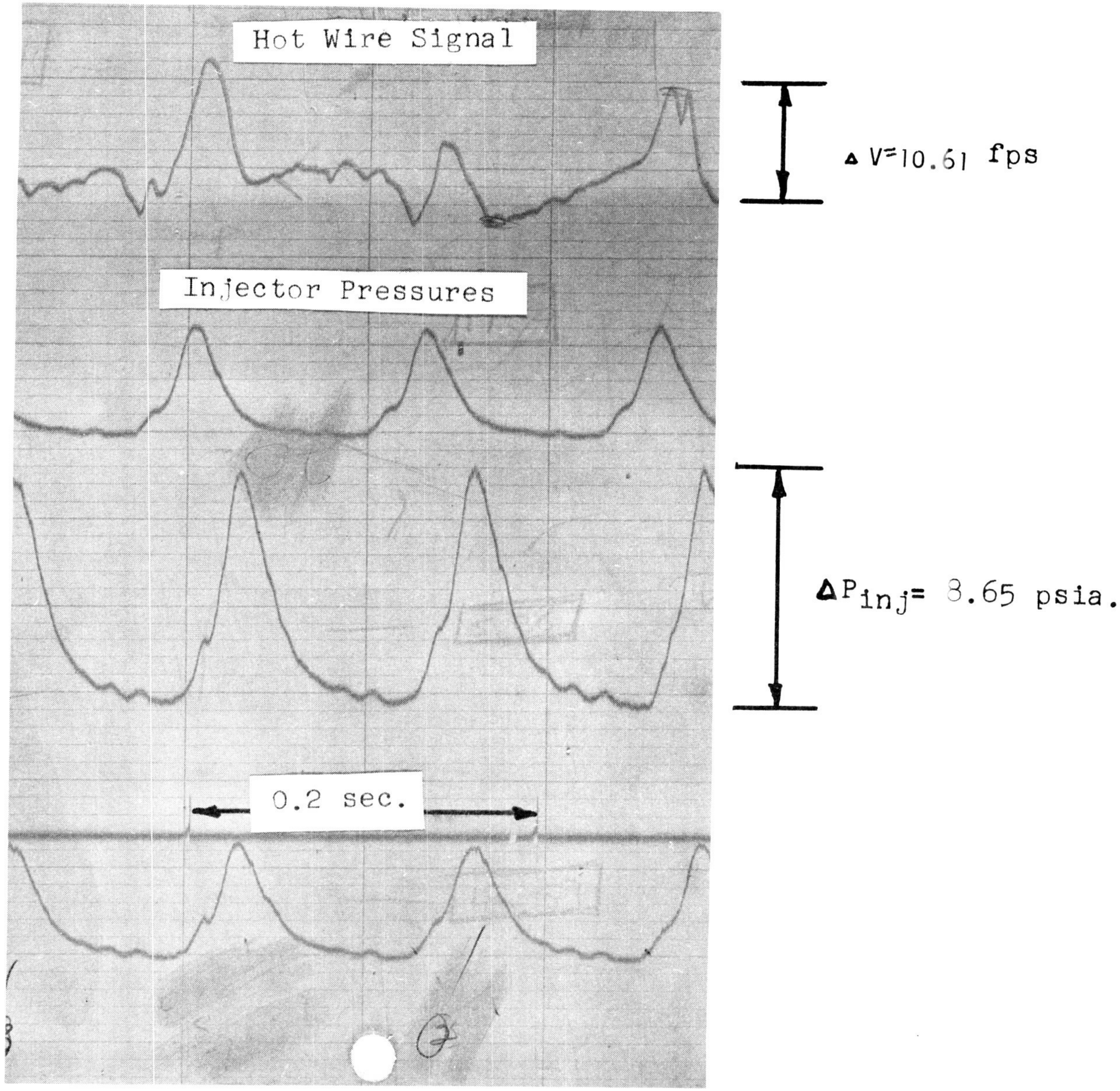
Oscillograph-41.5 cps

Figure 18D-Test Results, Config. Au-83 fps



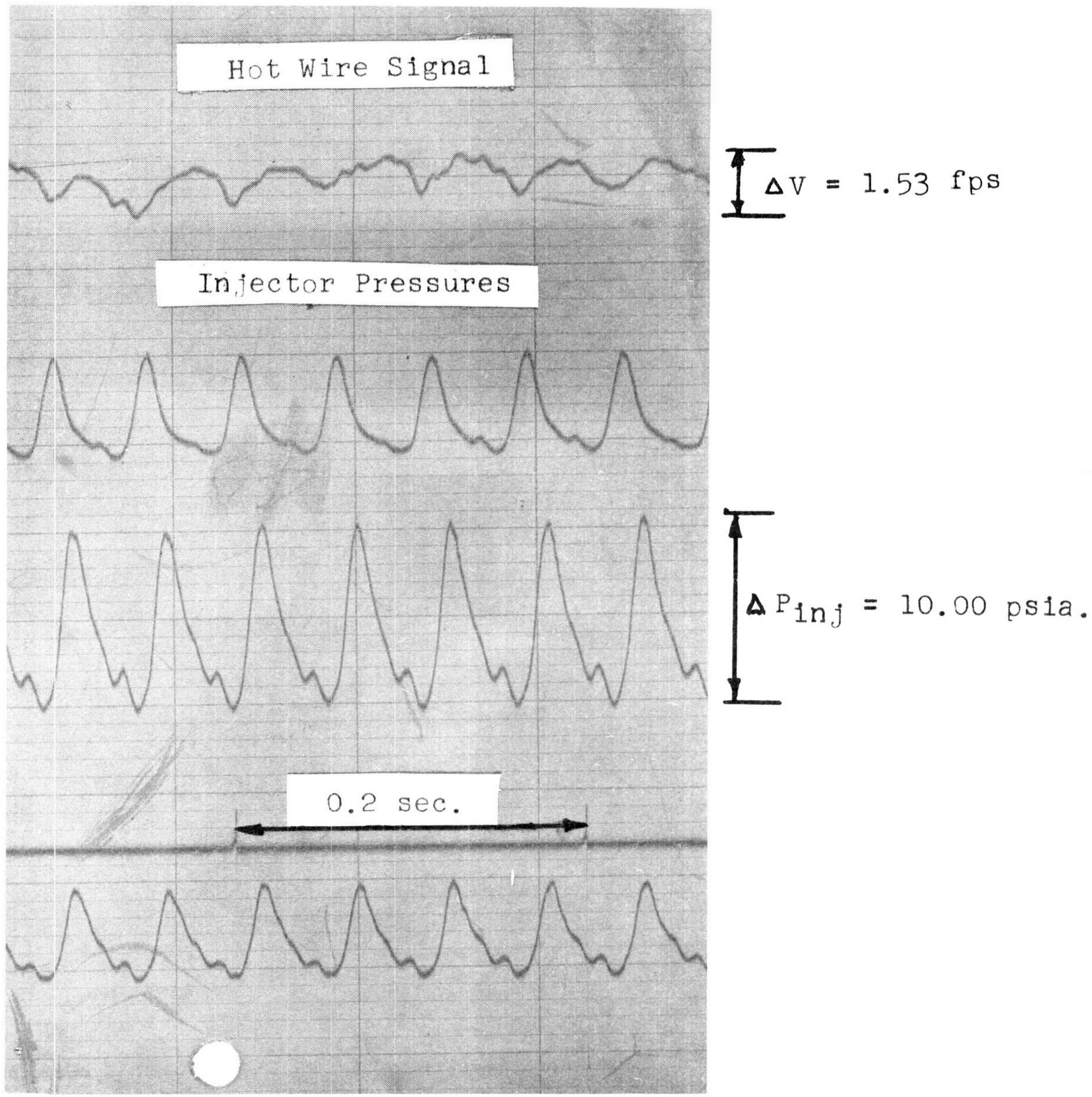
Oscillograph-54.0

Figure 18E-Test Results, Config. Au-83 fps



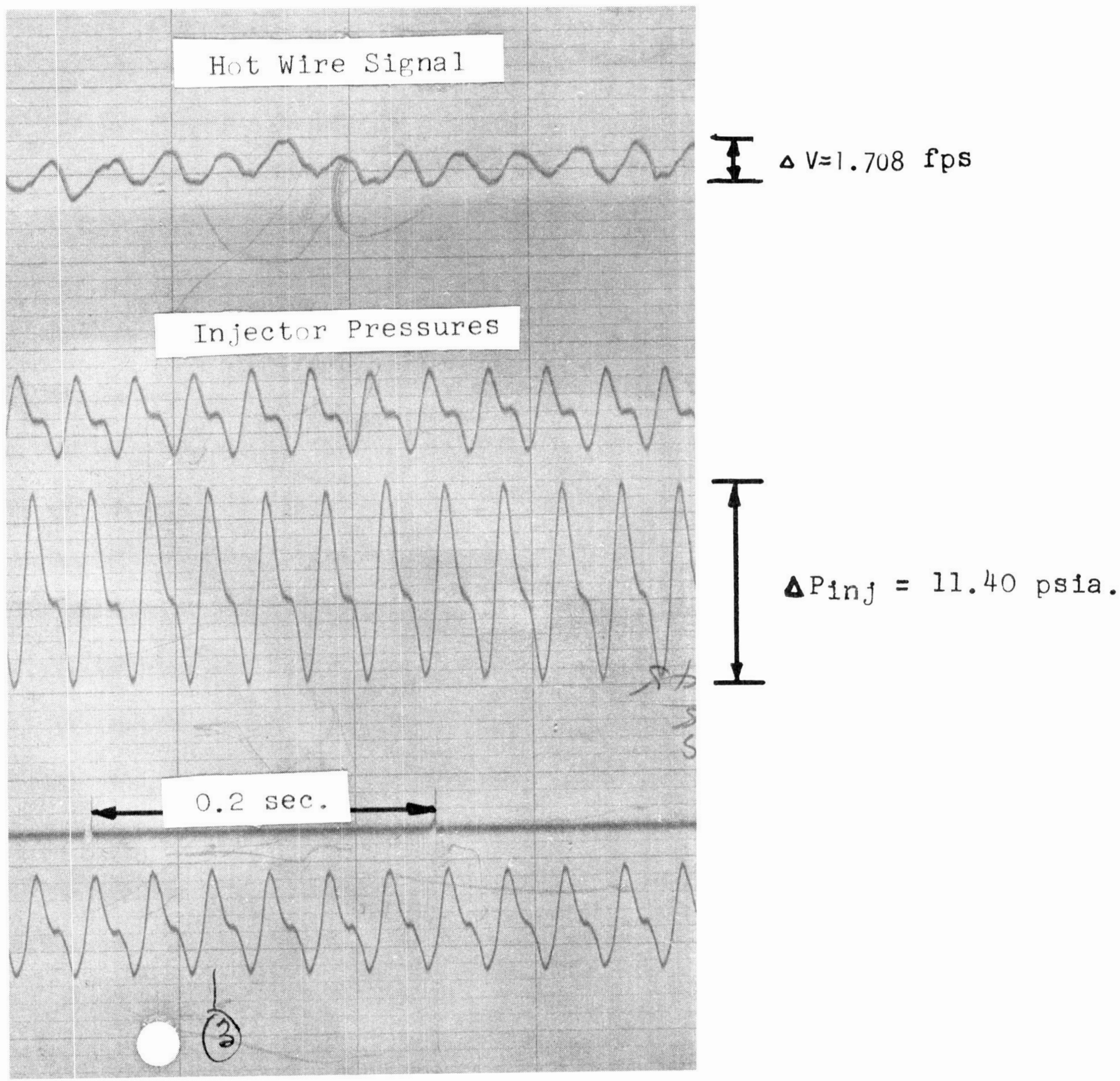
Oscillograph-7.5 cps.

Figure 19-Test Results, Config. Au-83 fps



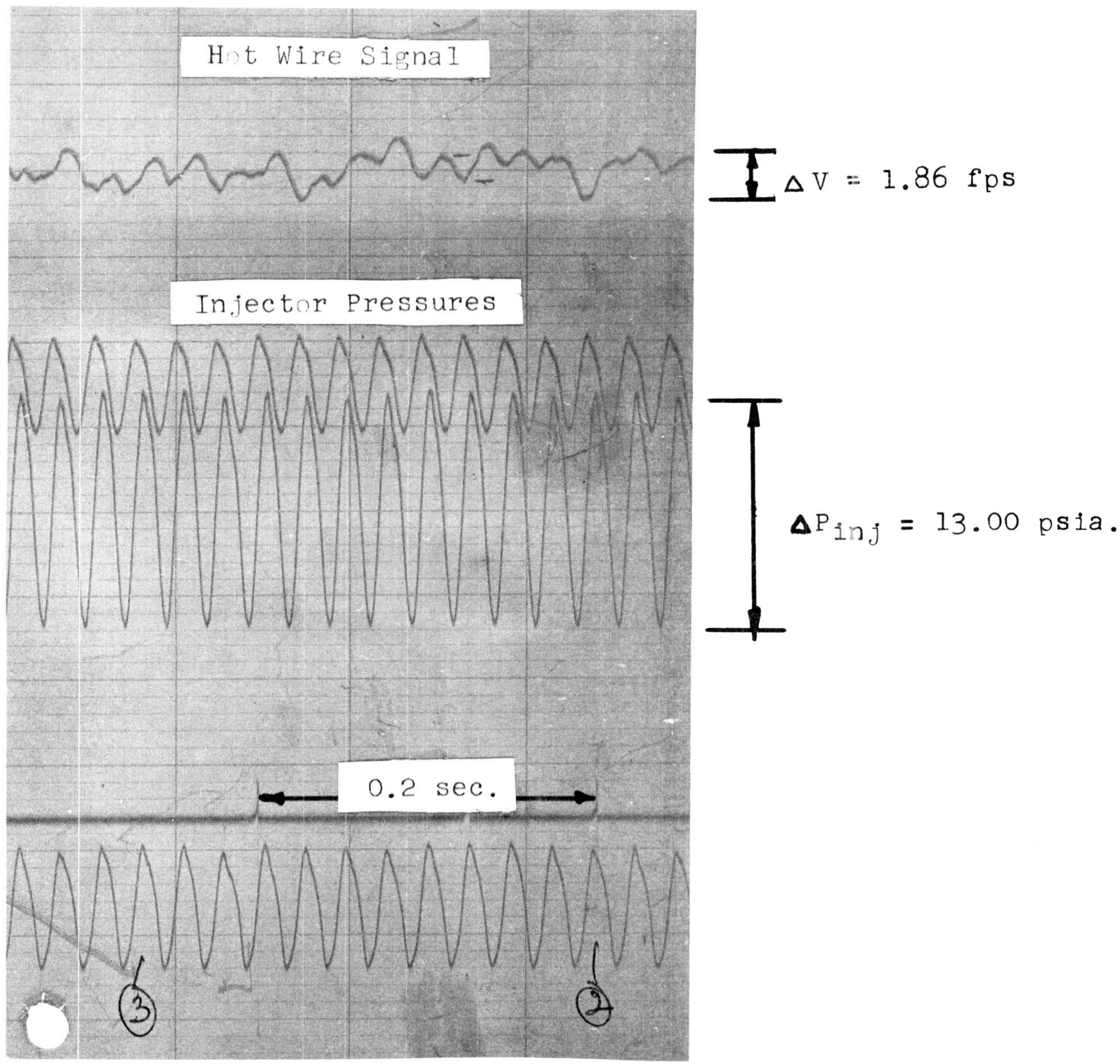
Oscillograph-18.2 cps.

Figure 19B-Test Results, Config. Au-83 fps



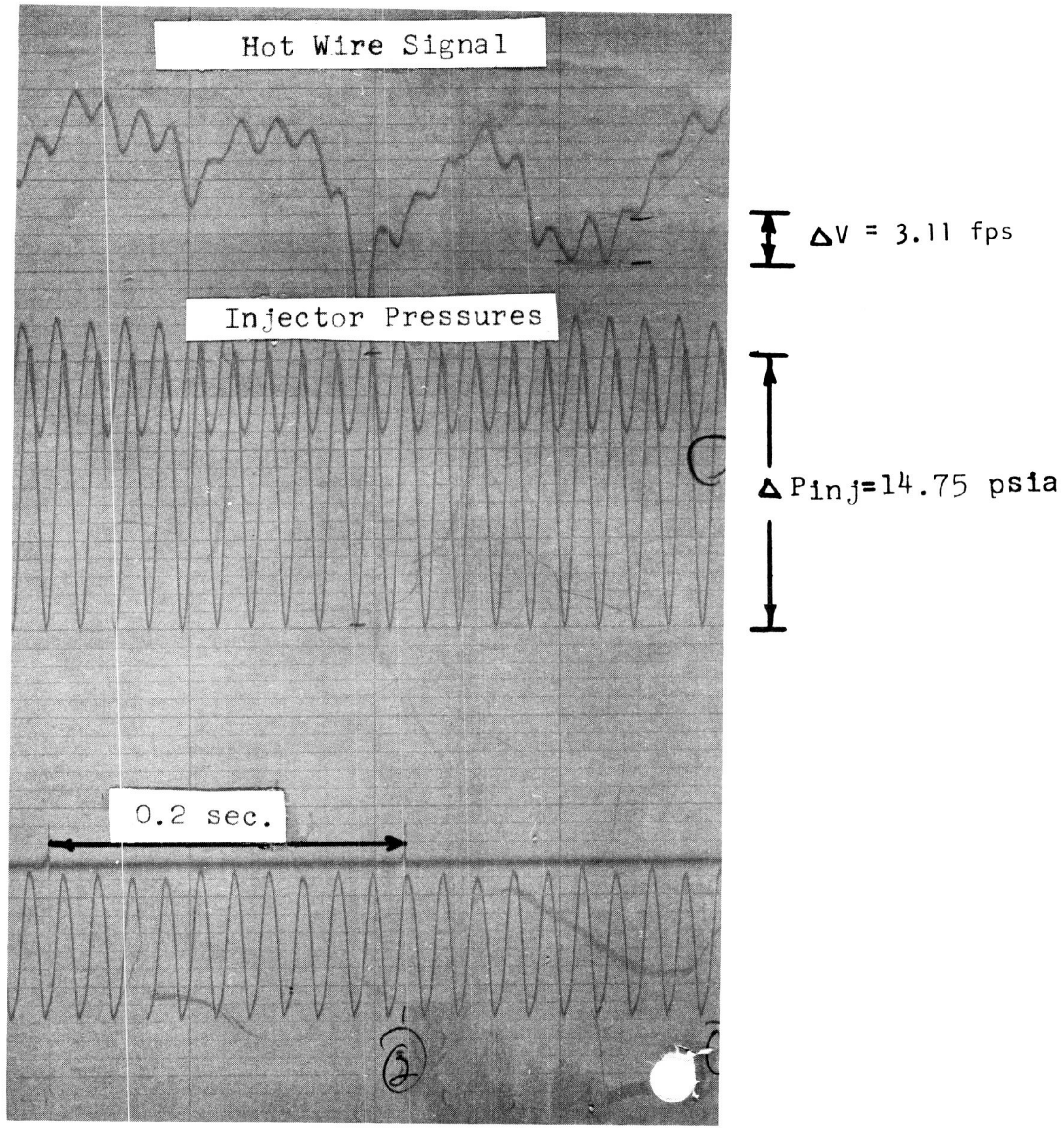
Oscillograph-28.2 cps.

Figure 19C-Test Results, Config. Au-83 fps



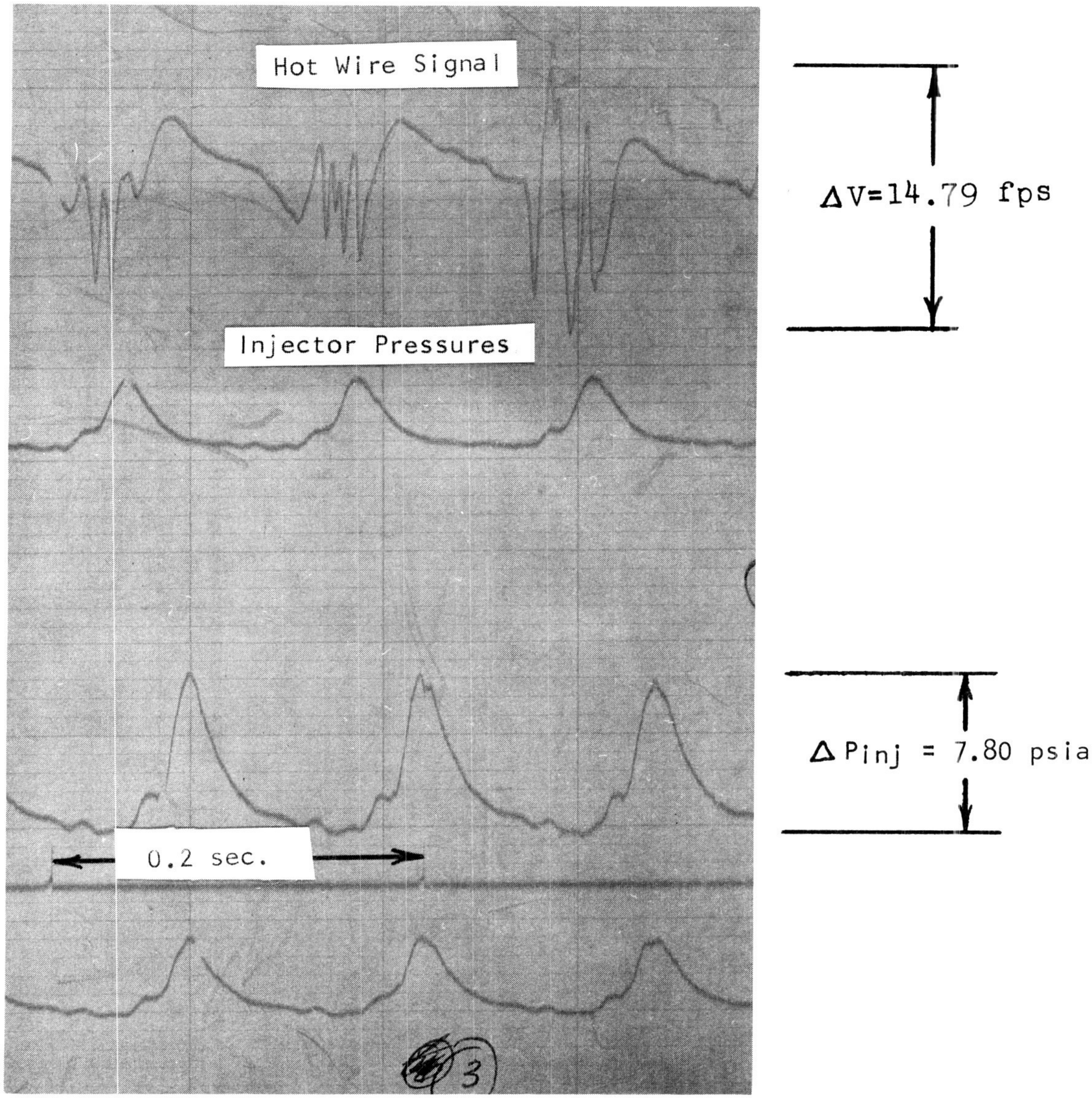
Oscillograph-41.0 cps.

Figure 19D-Test Results, Config. Au-83 fps



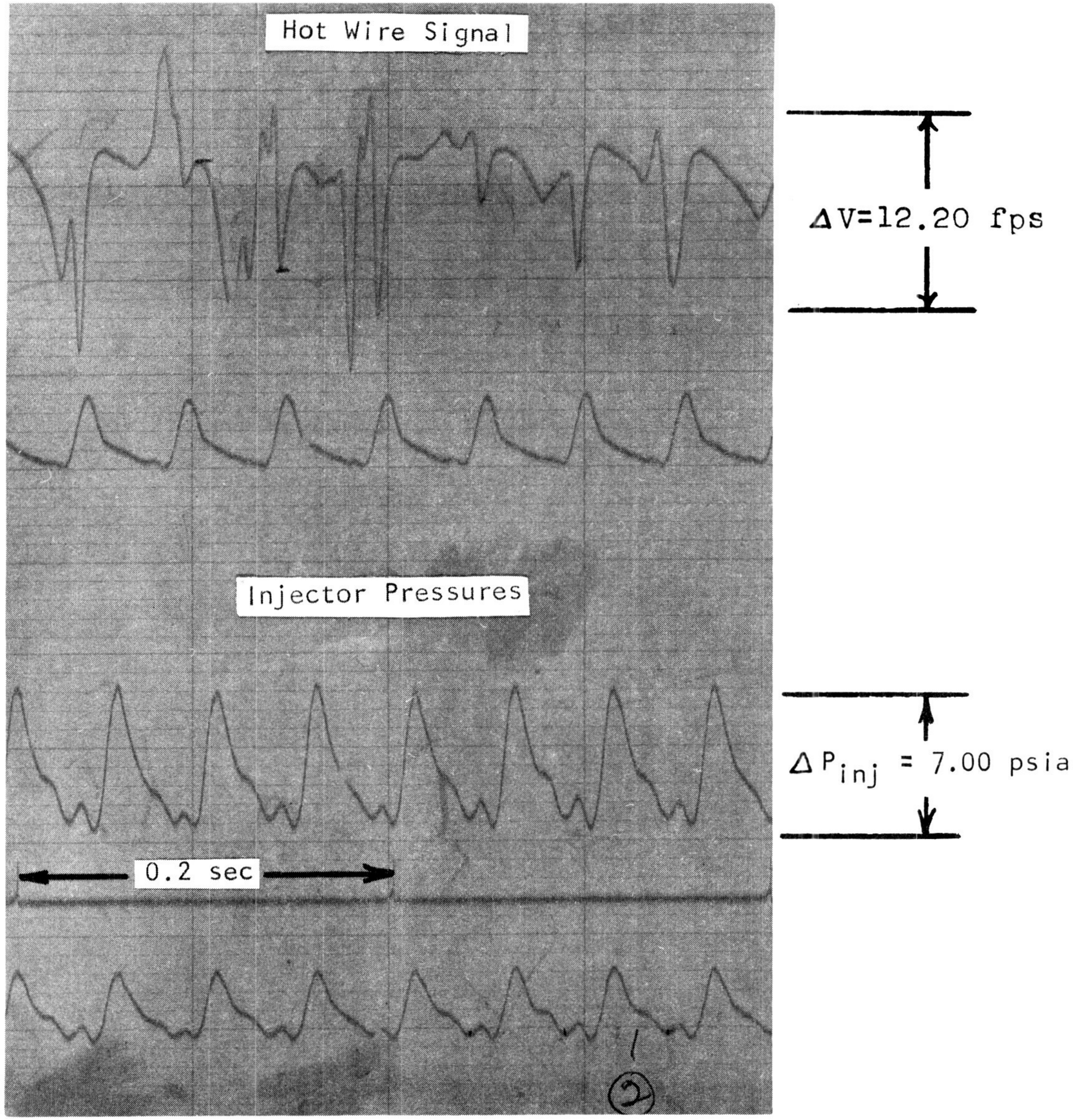
Oscillograph-51.5 cps.

Figure 19E-Test Results, Config. Au-83 fps



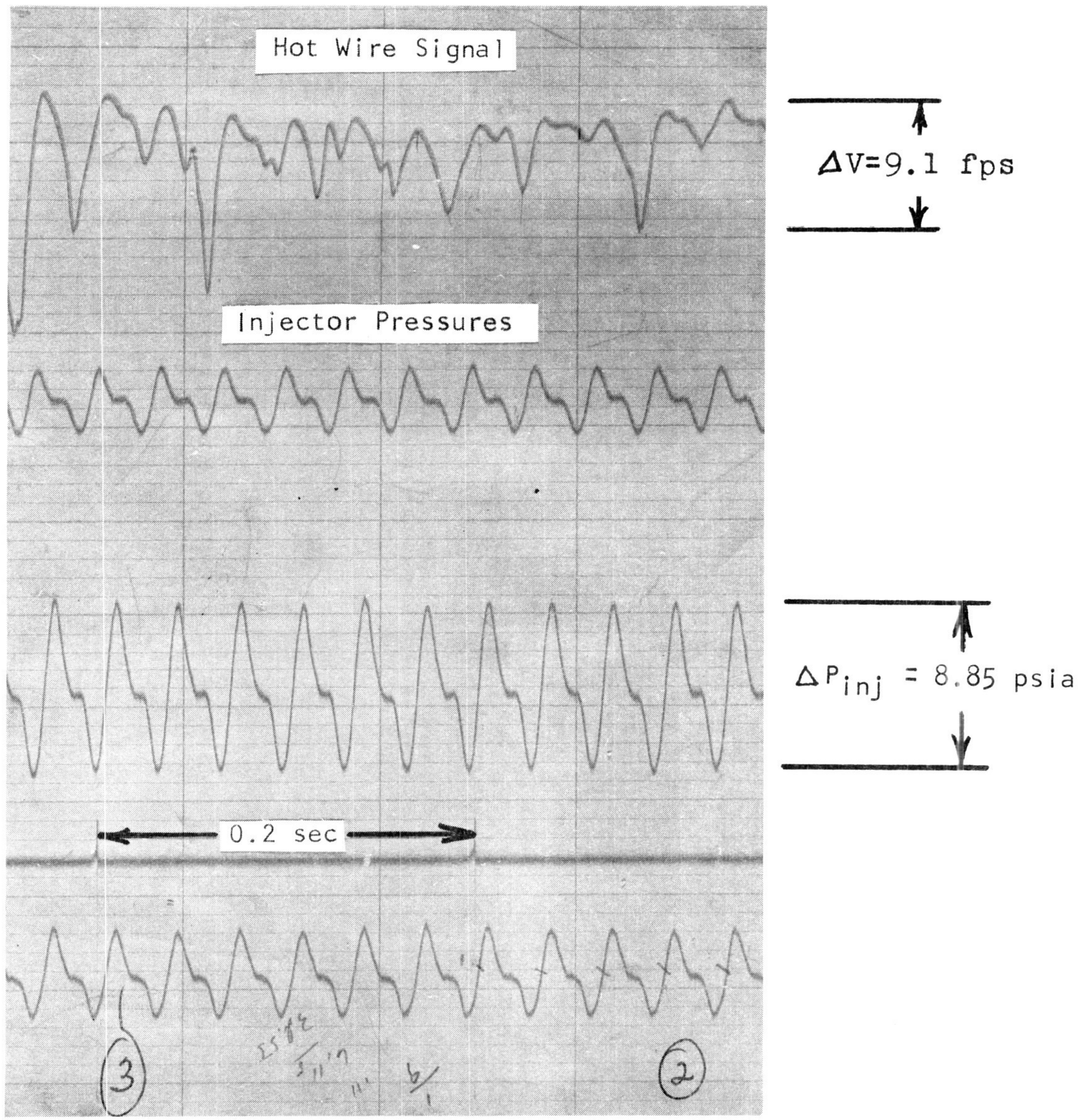
Oscillograph - 8.0 cps

Figure 20A-Test Results, Config. Au-83 fps



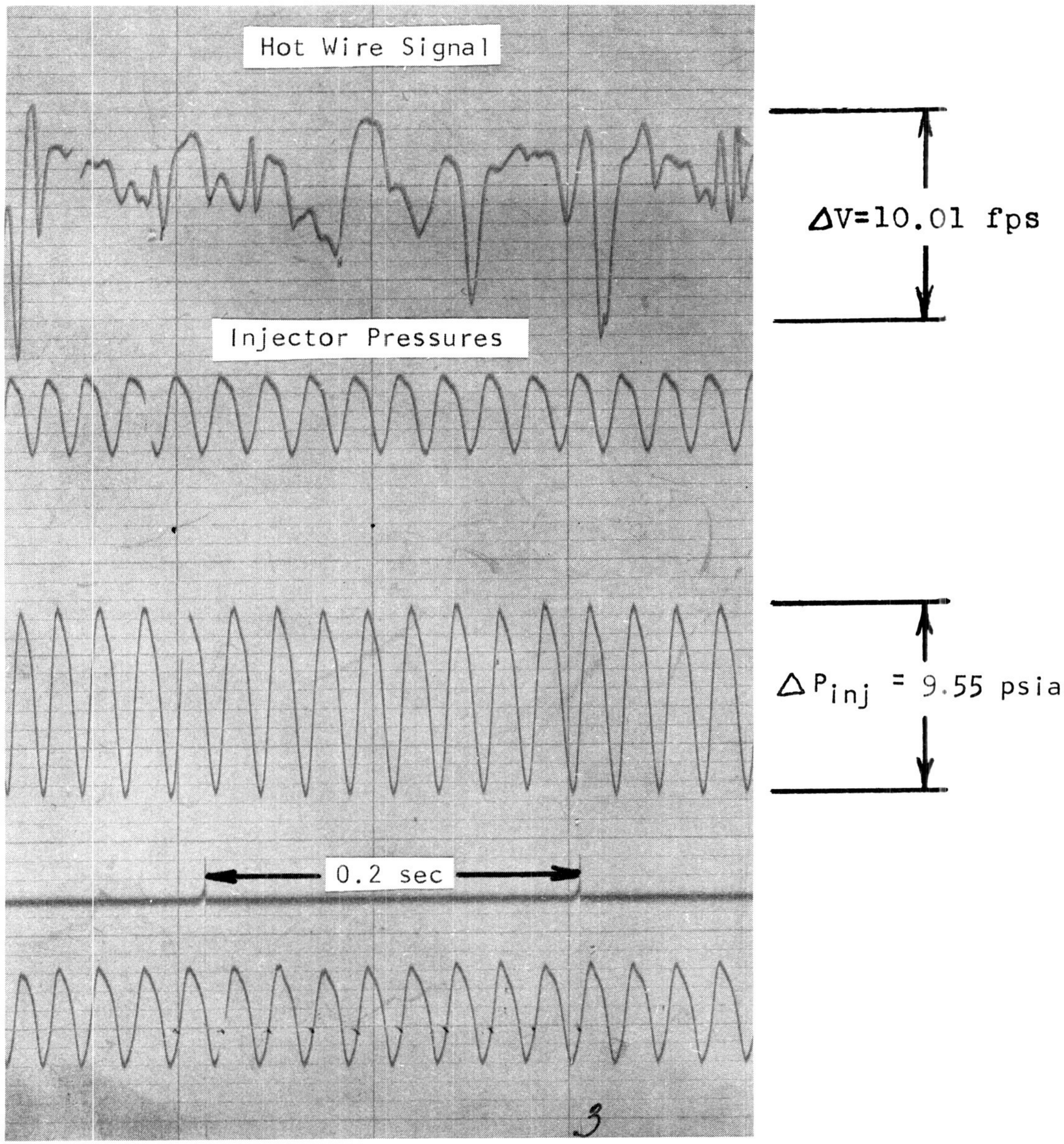
Oscillograph - 18.85 cps

Figure 20B-Test Results, Config. Au-83 fps



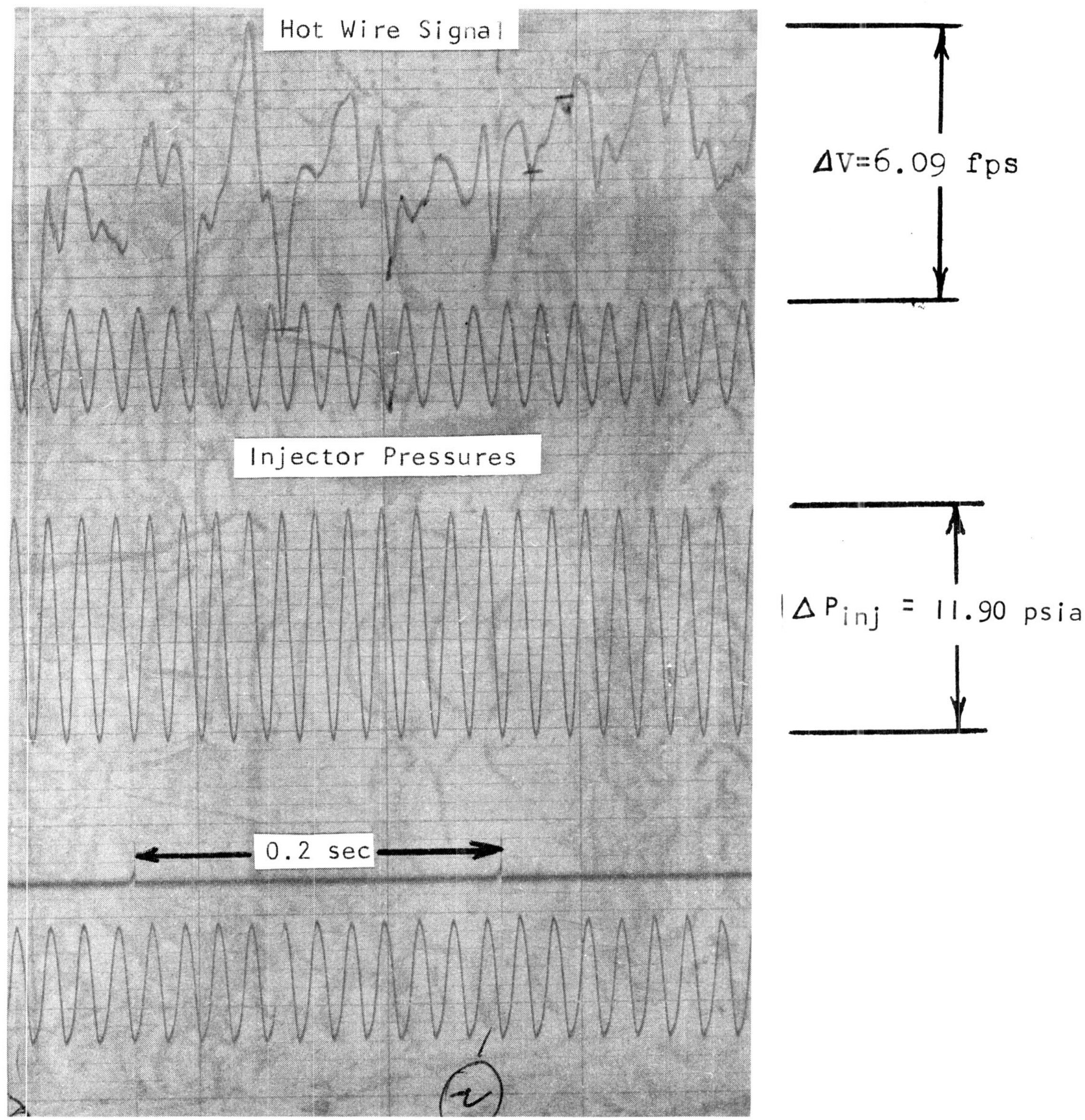
Oscillograph - 30.5 cps

Figure 20C-Test Results, Config. Au-83fps



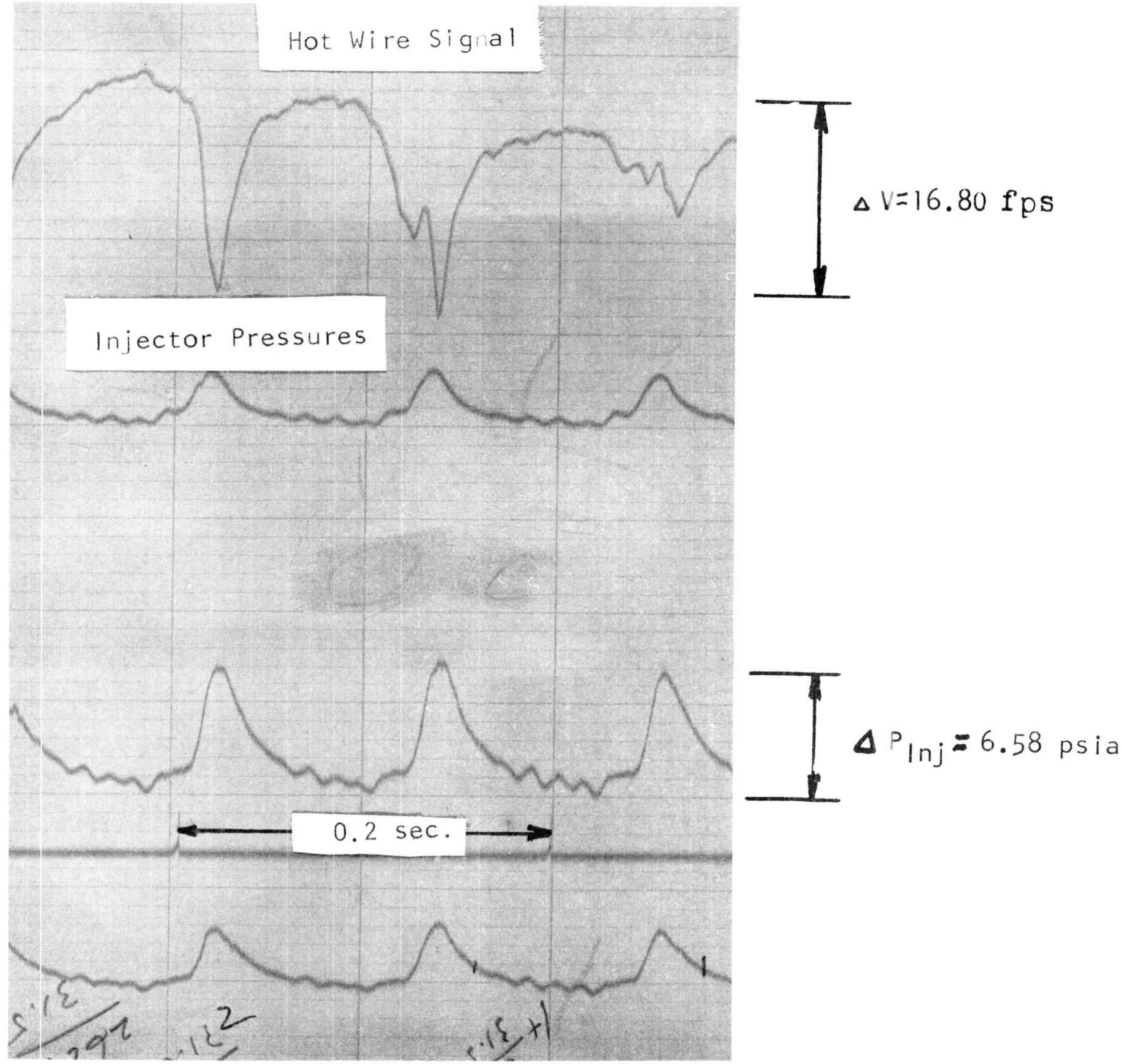
Oscillograph - 41.7 cps

Figure 20D-Test Results, Config. Au-83



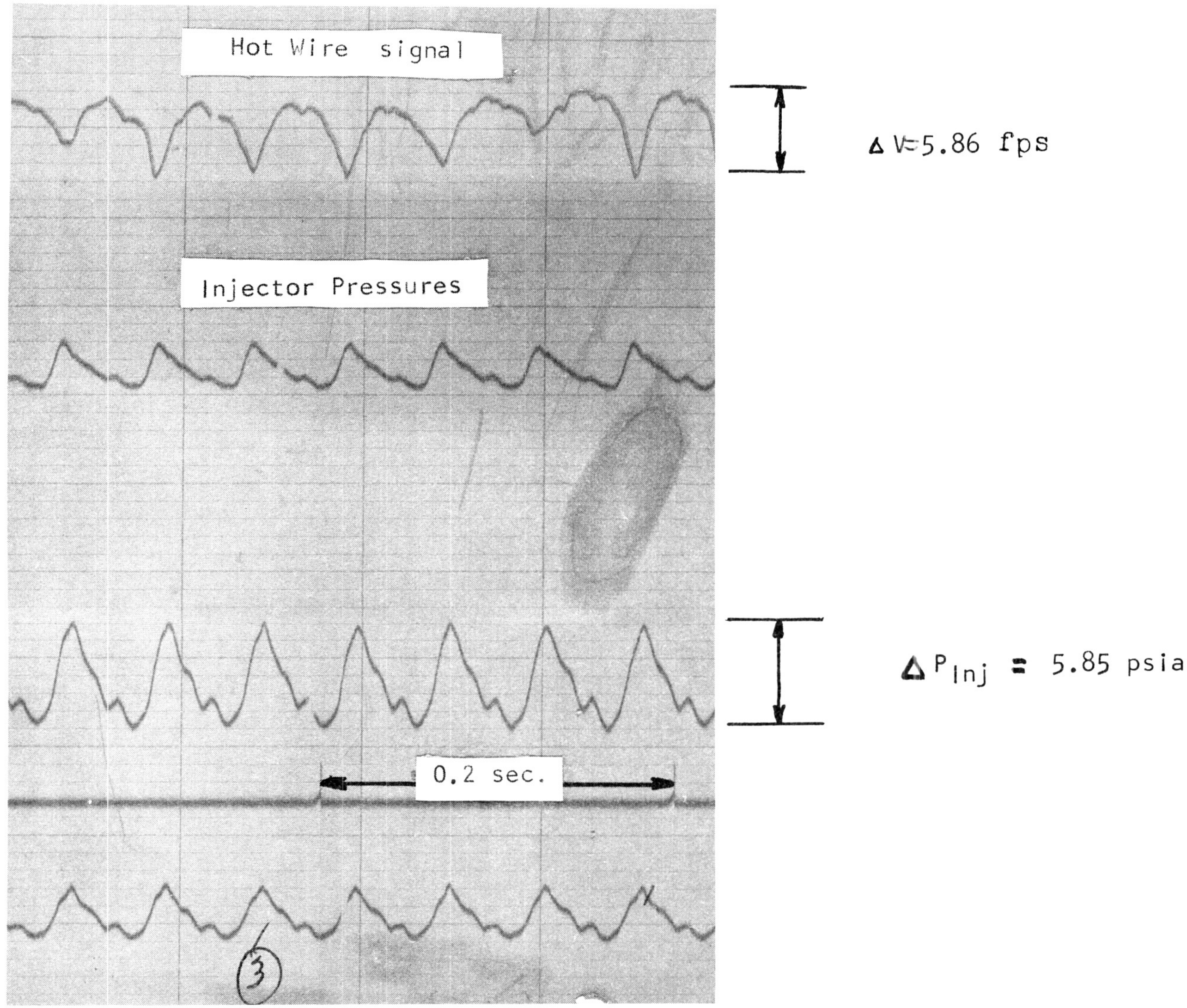
Oscillograph - 55.0 cps

Figure 20E-Test Results, Config. Au-83 fps



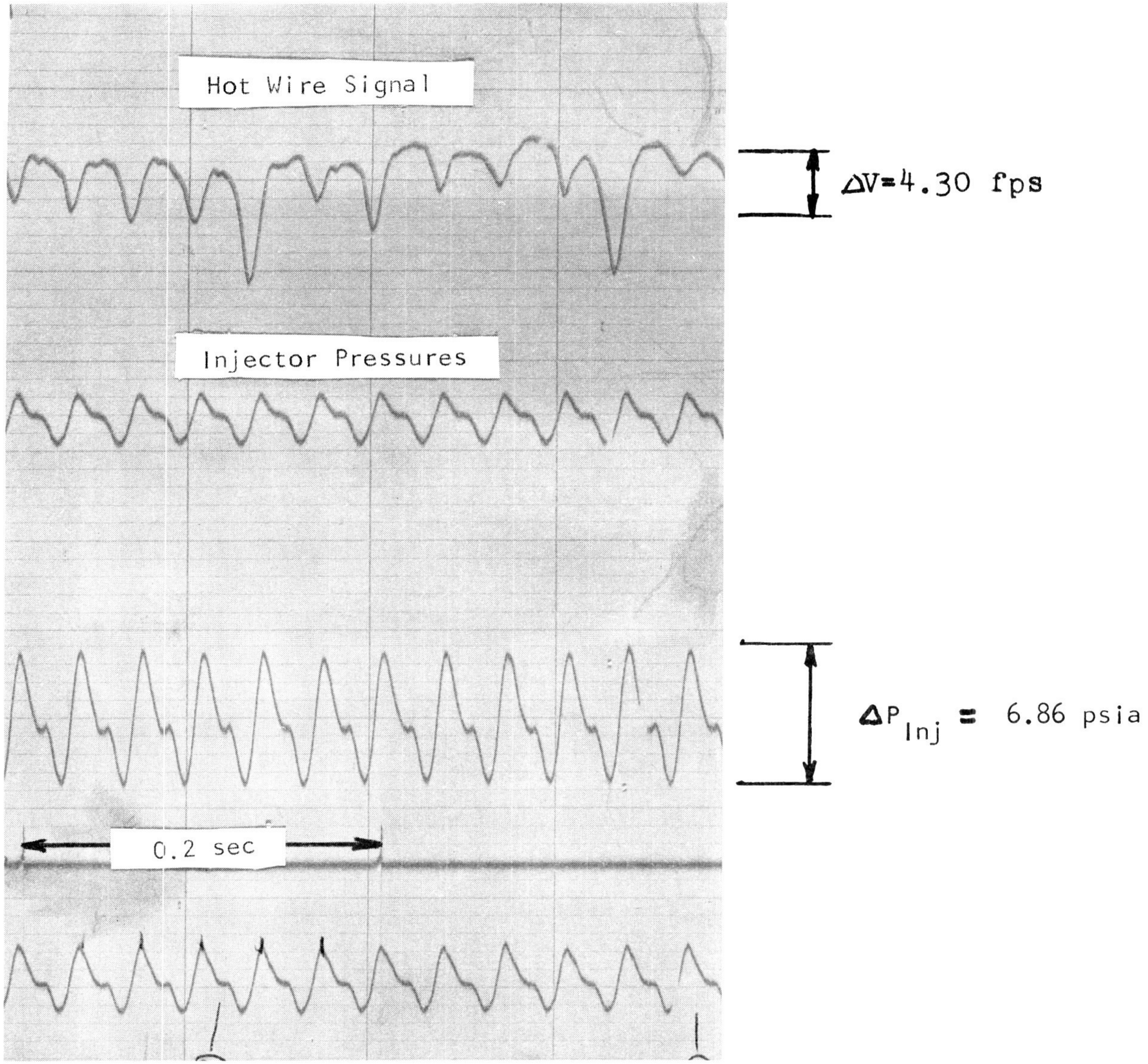
Oscillograph -8.33 cps

Figure 21A-Test Results, Config. Au-83 fps



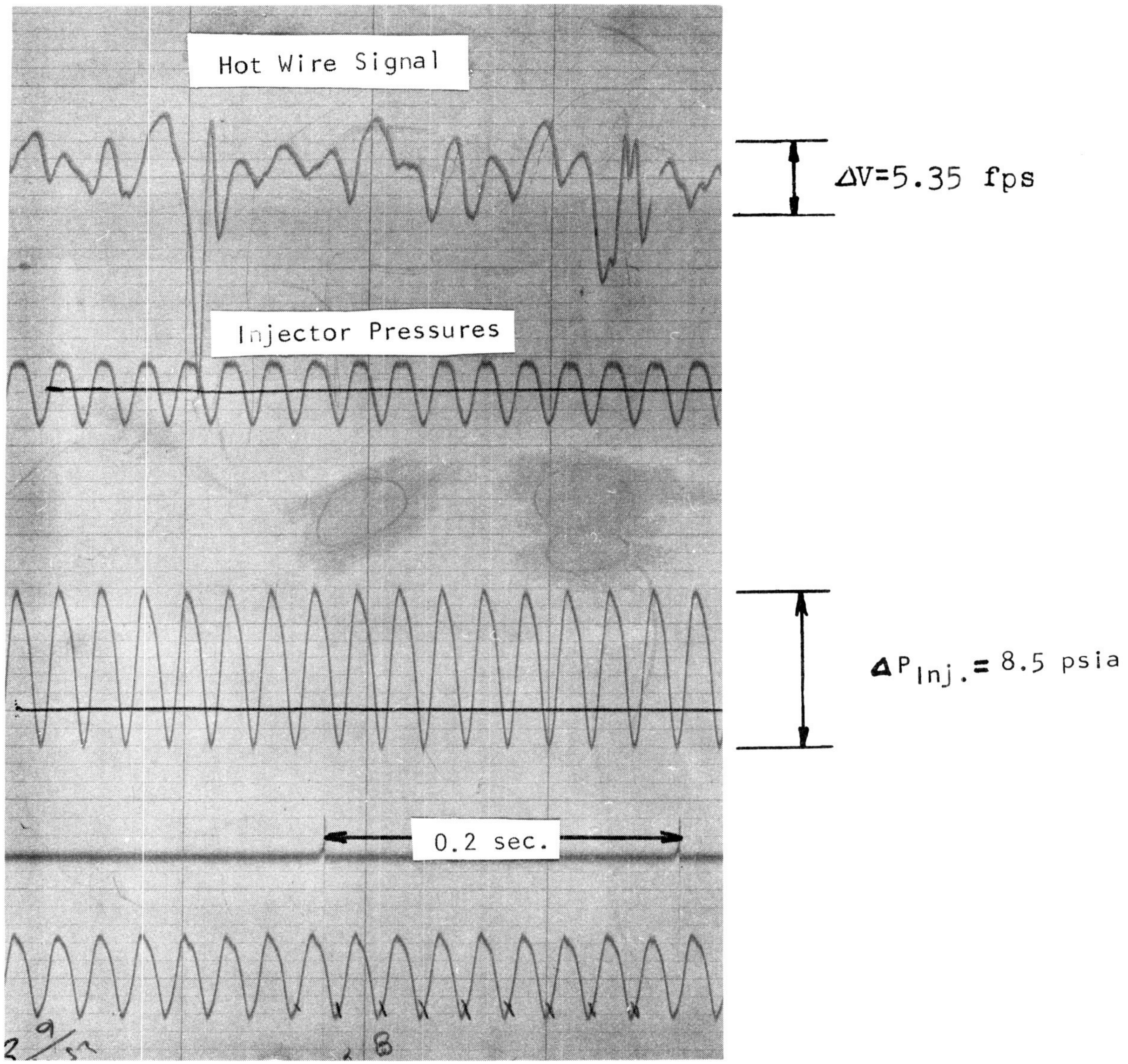
Oscillograph - 18.6 cps

Figure 21B-Test Results, Config. Au-83 fps



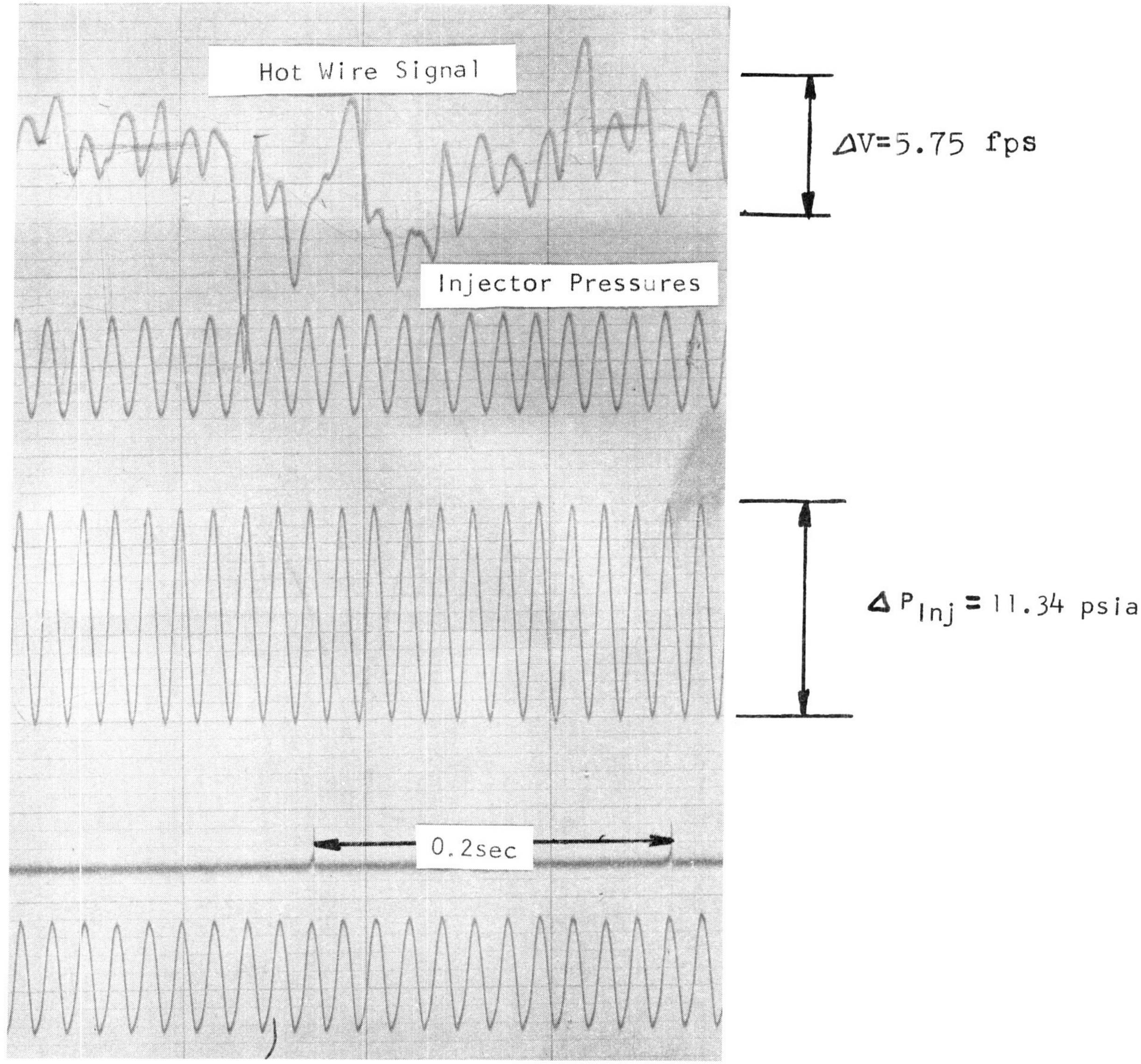
Oscillograph - 29.4 cps

Figure 21C-Test Results, Config. Au-83 fps



Oscillograph - 42.1 cps

Figure 21D-Test Results, Config. Au-83 fps



Oscillograph - 55.0 cps

Figure 21E-Test Results, Config. Au-83fps

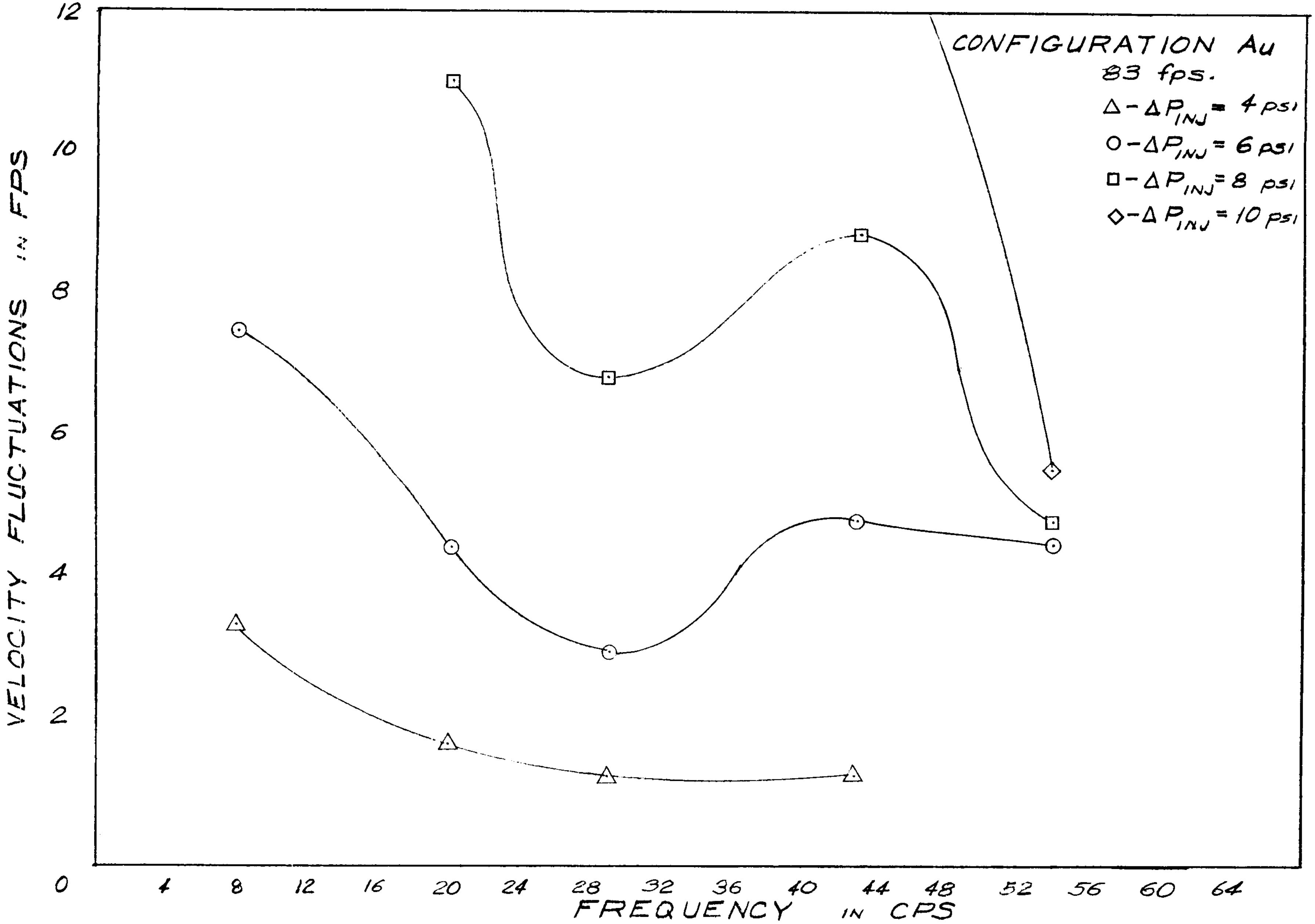


Figure 22 - Frequency Response versus Velocity Fluctuations

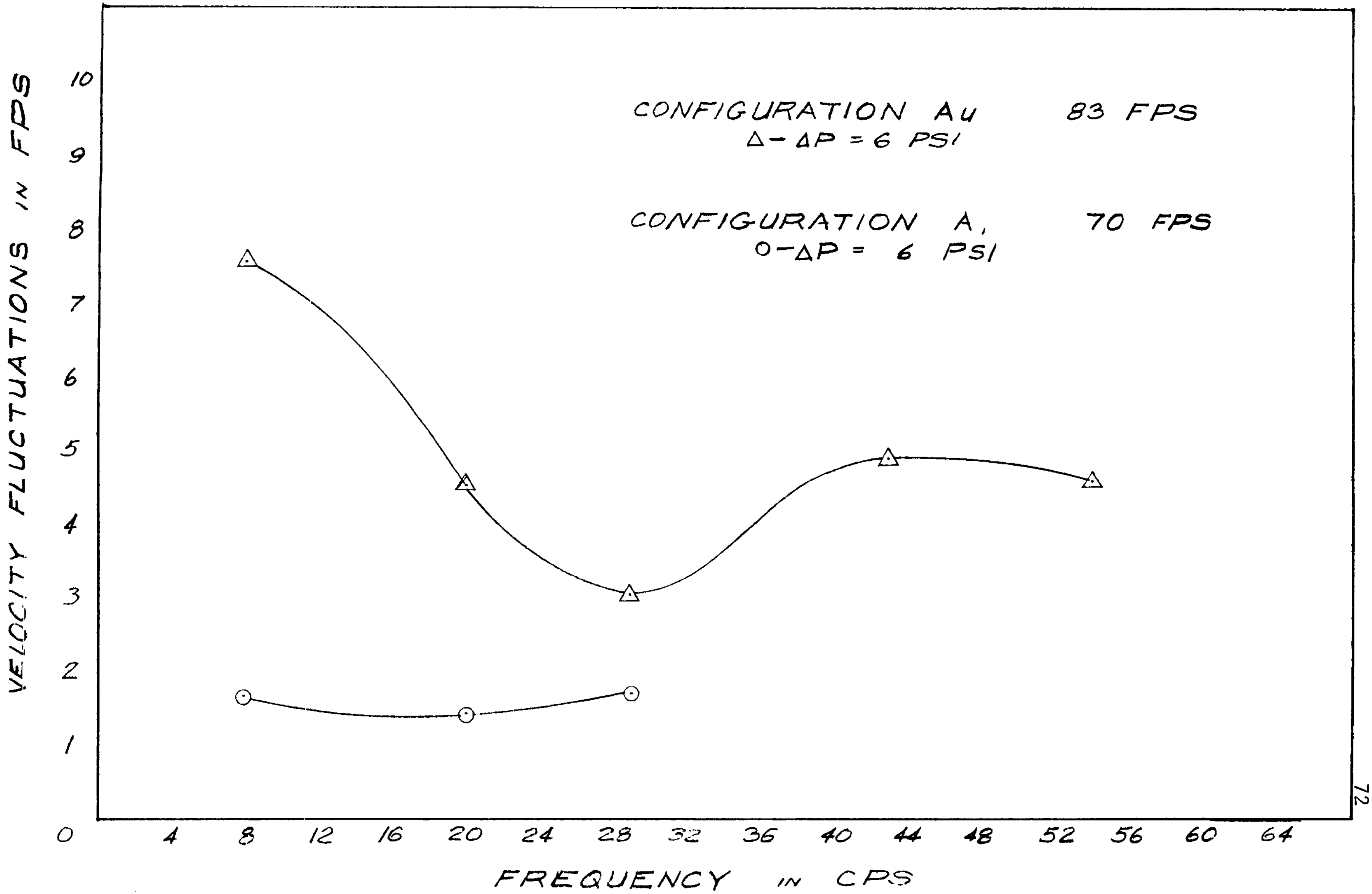


Figure 23 - Injector Efficiency Comparison

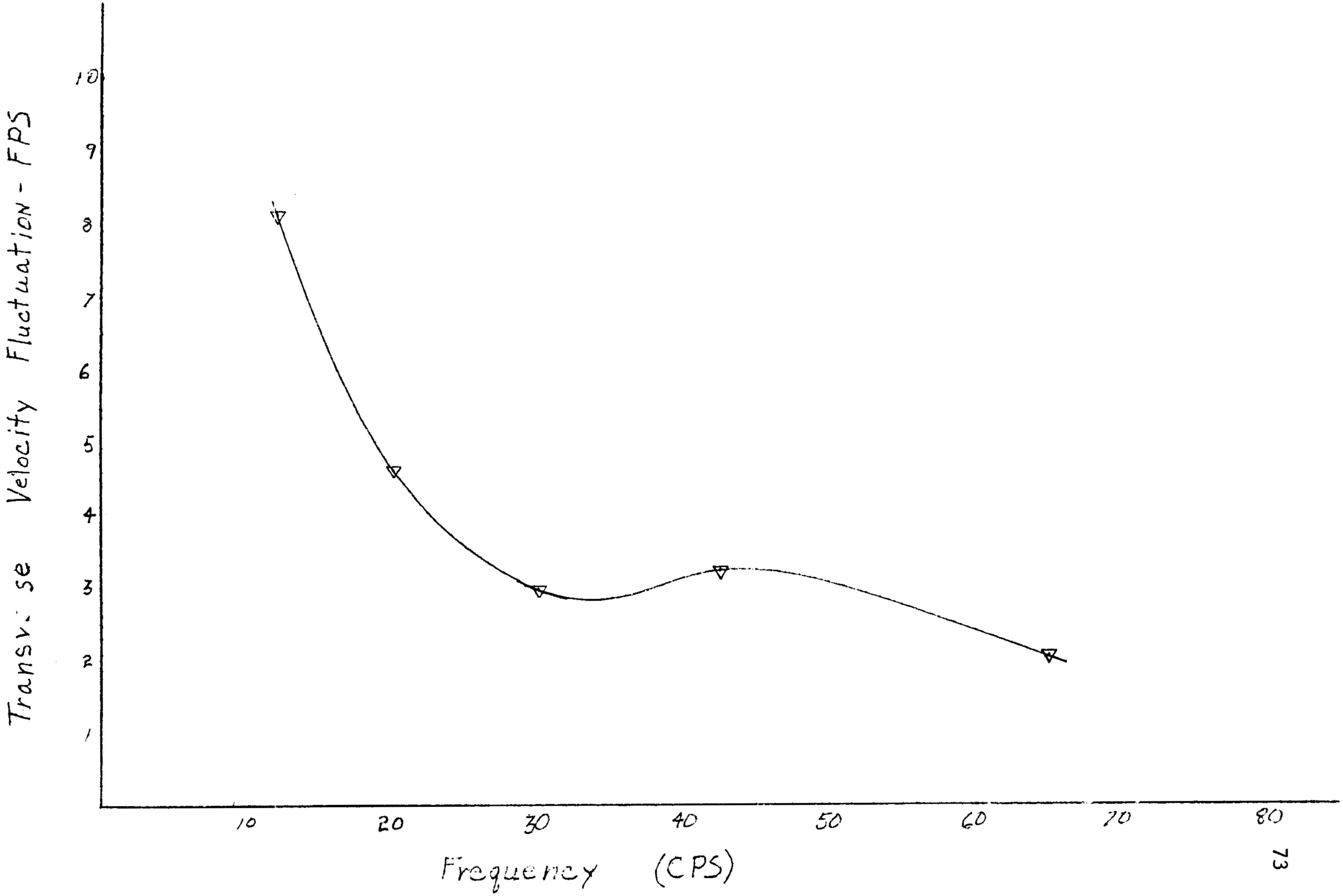


Figure 24-Transverse components of Two-Dimensional Gusts